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A TECHNIQUE FOR DESIGNING
ACTIVE CONTROL SYSTEMS FOR
ASTRONOMICAL-TELESCOPE MIRRORS

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# A TECHNIQUE FOR DESIGNING ACTIVE CONTROL SYSTEMS FOR ASTRONOMICAL-TELESCOPE MIRRORS

By W. E. Howell and J. F. Creedon Langley Research Center

#### SUMMARY

This paper considers the problem of designing a control system to achieve and maintain the required surface accuracy of the primary mirror of a large space telescope. Control over the mirror surface is obtained through the application of a corrective force distribution by actuators located on the rear surface of the mirror. The design procedure is an extension of a modal control technique developed for distributed parameter plants with known eigenfunctions to include plants whose eigenfunctions must be approximated by numerical techniques. Instructions are given for constructing the mathematical model of the system, and a design procedure is developed for use with typical numerical data in selecting the number and location of the actuators.

Two techniques for treating disturbances to the plant are discussed. These two techniques, which treat the errors as deterministic and uncorrelated, respectively, are examined from the standpoints of sensitivity to various mirror errors, determining the number of actuators required, and means of finding the best locations. For the deterministic case it was found that the "best" actuator locations (those locations which will minimize the steady-state error) are very sensitive to the error distribution. In addition, these locations can presently be found only by exhaustive searches of all possible actuator locations, and the number of actuators required for a specific mirror and specific error can only be estimated after much computer time is used. In practice the error distribution over the mirror surface would be expected to change with the telescope attitude relative to the sun. Also, the exact nature of the mirror errors will be time varying and will not, in any case, be known very precisely. For these reasons it is not recommended that the errors be treated deterministically. In addition, when the errors at any particular time are treated as uncorrelated random variables, the actuator locations are much less sensitive to specific variations in error distribution, an estimate of the number of actuators required to produce a desired reduction in figure error can easily be made, and locations which will yield results near the estimated figure accuracy can be found in a reasonable manner. Thus, at present this technique is preferred even though it requires more actuators than the deterministic method for a specific assumed error.

Several numerical examples are presented for a 76-cm-diameter (30-inch), thin spherical mirror and the computer program to implement the design procedure is given in an appendix. The results include a comparison of the modal control law and an optimal (least-squares) control law. The results of this comparison indicate that not much performance is to be gained by the added complexity of this optimum control law.

#### INTRODUCTION

One of the most fundamental problems associated with orbiting a large, diffraction-limited telescope of the size and type discussed in reference 1 is that of manufacturing, figuring, and maintaining the figure of the large primary mirror. Many factors such as initial figuring errors, the change from 1g to 0g, and changing temperature gradients on the mirror while in orbit make conventional techniques of figuring and supporting telescope mirrors unsuitable. An alternate approach has been developed in which the mirror is actively controlled by first sensing figure errors on the primary mirror and then nulling them by properly deforming the mirror. This technique (ref. 2) has been successfully applied to a 76-cm-diameter (30-inch), 1.27-cm-thick  $(\frac{1}{2}$ -inch) mirror with an initial error of 1/2 wavelength rms ( $\lambda$  = 0.6328  $\mu$ m). By using 58 actuators, the mirror was controlled to a figure accuracy of better than  $\lambda$ /50.

Since the time of the investigation reported in reference 2, consideration has been given to the application of a modal control technique to a class of mirrors. The modal control technique represents the plant to be controlled in terms of the eigenvalues and eigenfunctions of the linear differential operator which describes the behavior of the plant. In reference 3, this technique was applied to distributed parameter plants whose eigenvalues and eigenfunctions could be obtained in closed form. In many practical examples, however, the required eigenfunctions are not available. For the mirror, for example, the restrictions of practical mounts (boundary conditions) and the existence of holes in the center of the primary mirror used in Cassegrain telescopes preclude obtaining the required eigenfunctions in closed form. Estimates of these functions must be obtained via numerical approximation techniques. The purpose of this paper is to set forth for such a system a design procedure based on the use of the modal control law described in reference 3. First, the modal control concept is explained, the control system described, and the analysis procedure set forth. Certain specific details, such as accounting for the pad effects and the treatment of initial or expected error, are then covered. Numerical data for the 76-cm-diameter (30-inch) mirror are given and examples are presented. Appendix A contains a listing of the computer program; appendixes B, C, and D, eigenvector listings and diagrams and eigenvalue listings for the mirror; appendixes E and F, several examples of actuator placement and resultant mirror errors.

# SYMBOLS

Values in the body of the paper are given both in SI Units and U.S. Customary Units. The measurements and calculations were made in the U.S. Customary Units. The values in the appendixes are in U.S. Customary Units and are consistent with the program in appendix A.

A	area of mirror
aį	ith modal coefficient which expands P in terms of the mode shapes (see eq. (35))
aN	$N \times 1$ vector of coefficients of the force distribution in the modal domain which corresponds to the controlled modes
aR	$R\times 1~$ vector of coefficients of the force distribution on the mirror; these coefficients arise from the action of the $N$ actuators
С	$M\times 1$ -vector which is the sum of the control system displacements and the disturbances in the modal domain; C is partitioned into $C^N$ and $C^R$
$C^{\mathbf{M}}$	figure sensor estimate of C
$C_N$	$N \times 1$ vector which contains the elements of $C$ which are being controlled
Ĉ <sup>N</sup>	figure sensor estimate of the N modal coefficients corresponding to the controlled modes
$c_{ss}^{N}$	steady-state or final value of CN
$C^{R}$	$R \times 1$ vector which contains the remaining elements of $C$
$c_{\mathbf{s}\mathbf{s}}^{R}$	steady-state or final value of CR
$D_{M}$	$N \times N$ diagonal matrix which contains the control system compensation (also referred to as the diagonal controller)
E	performance index under the assumption of uncorrelated errors

E for a particular set of N actuators  $\mathbf{E}_{\mathbf{N}}$ f frequency M < N matrix which converts the actuator forces to modal coefficients H recaining the dimensions of force; H is partitioned into HN and HR  $H^{N}$ N × N matrix which contains the rows of the H matrix corresponding to the N modes being controlled  $_{\rm H}$ R **H** × N matrix containing the remaining elements of the H matrix hij ijth element of the H matrix J,J\*,J1 performance indices K gain constant total number of modes (eigenvectors) used to model the mirror M diagonal matrix of elemental masses  $\Delta m_i$ m total mass of mirror  $m_t$ mass of ith element of the structural model  $\Delta m_i$ number of actuators or number of controlled modes N P total force distribution on the mirror from N actuators vector of disturbance coefficients in the modal domain q modal error coefficient of the ith mode  $q_i$  $q^{\mathbf{M}}$ the  $M \times 1$  vector q

 $N \times 1$  vector of disturbances in the modal domain which correspond to the

 $q^N$ 

controlled modes

qR	$R\times 1$ -vector of disturbances which remain after $q$ is partitioned into $q^{\textstyle N}$ and $q^{\textstyle R}$
R	remaining modes, R = M - N
s	Laplace operator
U	M × M matrix of eigenvectors
w	$M \times 1$ vector of mirror errors at the grid points
$w_i$	figure error of the mirror at the ith grid point
x,y,t	x,y coordinates on mirror at time t
Z	coordinate axis directed (positive) along the optical axis
$\alpha^{N}$	$N \times 1$ vector of forces applied to the mirror surface ( $\alpha = \alpha^N$ )
$oldsymbol{eta_j}$	force distribution over the pad area of the jth actuator
Г	area over which the pads act
$\epsilon_{\mathbf{i}}$	structural damping of the ith mode
Λ	M × 1 vector of eigenvalues
λ	wavelength of light
$\xi^{\mathbf{M}}$	figure sensor error in determining $C^{\mathbf{M}}$
ρ	density of the mirror expressed in terms of its area
$\sigma_{\mathbf{q_i}}^{2}$	variance of the ith modal error
au, au', au''	time constants
$\phi_{\mathbf{i}}^{\;\;2}$	defined by equation (59); under the assumption of uncorrelated errors, this

quantity gives the fraction of 'ne ith modal error which appears in the final

error

 $\phi_{iN}^2$   $\phi_i^2$  for a particular set of N actuators

 $\psi$  R × N matrix  $\Lambda^{R}H^{R}[\Lambda^{N}H^{N}]^{-1}$ 

ω natural frequency

#### Subscripts:

i general term of a vector

i,j general element of a matrix

M last calculated mode

N last mode or actuator under consideration

n nth term of a set

#### Superscripts:

estimate

T transpose of a matrix

#### CONTROL SYSTEM DESCRIPTION

#### The Modal Control Concept

The modal control concept, a applied to mirrors for use in orbiting telescopes, is treated in detail in reference 3, and design examples for flat plates are presented. For purposes of analysis in the present study, the mirror is considered to be a structure tied to a set of supports or mounts that prevent rigid-body motions. The elasticity of the mounts themselves may or may not be considered, depending upon the degree of sophistication of the analysis. (The analysis used throughout this paper considers the mounts to be rigid.) The modes of vibration of the mirror, subject to the constraints of the supports, are the modes used in the analysis. The mode shapes are referred to as eigenvectors of the mirror and the frequencies are the eigenvalues.

Generally the mode shapes and frequencies must be obtained by numerical methods since the solution of the governing partial differential equation is not available. The eigenvectors and eigenvalues of the structure that are used in this paper were obtained from a

numerical program (SAMIS, ref. 4) and have been checked by NASTRAN (ref. 5). These results have been verified experimentally (ref. 6). The eigenvectors obtained from the numerical program are tabulated in the U matrix (see appendix B), with column 1 denoting the first, or lowest frequency, eigenvector and each succeeding column denoting higher order mode shapes. The vector of eigenvalues  $\Lambda$  (see appendix D) is ordered with the lowest frequency first.

The finite-element model that was used in SAMIS is given in reference 7. This model was used to extract the first 58 eigenvectors and eigenvalues of the mirror. (See appendix D.) This set of eigenvectors and eigenvalues has been used throughout the analysis.

One motivation for using the modal control law was to allow the designer to decouple the dynamic behavior of the control system; another and more important aspect of this control law is that the mode shapes provide a hierarchy of errors that are likely to occur in practice. That is, the modes may be ordered in such a way that mode 1, or the fundamental mode shape, is more likely to occur than mode 2. Also, a measure of the relative amplitude is available by examining the eigenvalues of the two modes. That is, if the eigenvalues of modes 1 and 2 differ by a factor of n, the second mode will require about n times the input force disturbance to produce the same displacement error. This is just another way of saying that the mirror (plant) acts as a filter to high-order modes. The one exception to this is that careless initial polishing and figuring of the mirror could generate considerable error (as displacements) in the high-order modes. Conversely, this knowledge of the mirror should be used to avoid fabrication errors which will be particularly difficult to correct.

#### System Configuration

For the purposes of designing a control system for a mirror, the designer obtains a transformation from mirror surface deflections (or errors) to modal coefficients, which can be viewed as a coordinate transformation. That is,

$$\mathbf{q} = [\mathbf{U}]^{-1} \mathbf{W} \tag{1}$$

represents a transformation from the error at a set of points. Whover the surface of the mirror to a set of modal coordinates  $\,\mathbf{q}$ . Figure 1 shows a block diagram of the mirror, figure error sensor, and actuators as they appear in a finite modal representation. The mirror itself is mathematically represented by the five blocks (matrices) labeled  $\,\mathbf{H}^{N}$  and  $\,\mathbf{H}^{R}$ ,  $\,\mathbf{\Lambda}^{N}$  and  $\,\mathbf{\Lambda}^{R}$ , and  $\,\mathbf{U}^{M}$ . The superscripts  $\,\mathbf{N}$  and  $\,\mathbf{R}$  have the relationship

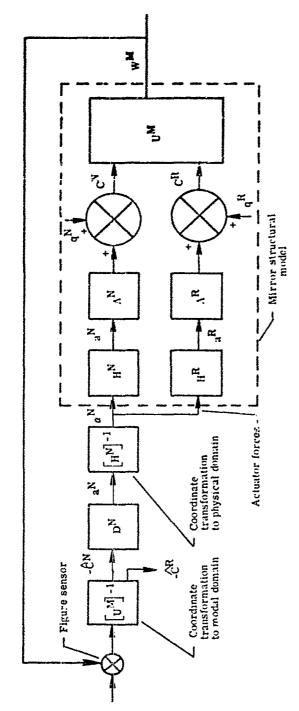


Figure 1.- Block diagram of mirror and control system.

. . . . where

N

mumber of modes used to model the mirror (although there are an infinite number of mirror modes, practical limitations require a finite number, and 58 will be used later for numerical evaluation)

number of actuators used (numerically equal to the number of controlled modes)

R remaining modes

In the physical world the actuator forces  $\alpha^N$  are translated directly into mirror tigure displacements. W(x,y,t); in the mathematical model the N forces are transformed by the  $H^N$  and  $H^R$  matrices into a set of force coefficients  $a^N$  and  $a^R$ , respectively, in the modal domain. These forces are then transformed by the  $\Lambda$  matrices into the modal coefficients of displacement. These coefficients, generated by the control system, are summed with the coefficients representing the error in the modal domain that previously existed on the mirror, and the result (denoted by  $C^N$  and  $C^R$ ) is transformed by  $C^M$  into the final displacement. W(x,y,t) according to the relationship

$$\left[ U^{M} \right] \left\langle \frac{C^{N}}{C^{R}} \right\rangle = W^{M}$$
 (2)

To combine this model into a control system requires a sensor to measure W(x,y,t). The sensor output is then changed into the modal coordinate system by the proper transformation  $\left[U^{\mathcal{M}}\right]^{-1}$ . Since N actuators can control only N modes, the subset of the N selected modes to be controlled is usually all that is generated. One would normally control only the first, or lowest. N modes.

The N selected modes are then fed through the dynamic compensation  $D^N(s)$  in which the proper gains and compensation are applied to each mode independently. If a type 1 system is used, as will be specified in the section entitled "Evaluation of Steady-State Errors," then each diagonal element of  $D^N$  corresponding to one channel of the decoupled controller will contain an integration. The output of  $D^N$ , denoted  $a^N$ , is still in the modal domain. In fact, this output is a set of modal coefficients which describe the desired force patterns to be distributed on the mirror. To change these to discrete forces, which is the way they must be applied to the mirror, the values of  $a^N$  must be

transformed by multiplying by  $\left[H^N\right]^{-1}$ . This matrix  $\left[H^N\right]^{-1}$  also accounts for the effect

of the physical mechanism through which the actuator applies a load to the plant. This completes the description of the control system which will be analyzed in later sections. For a more complete and rigorous discussion, see reference 3.

## Modal Representation of Figure Error

The modal control technique has been developed for mirrors whose modes, denoted by  $U_i(x,y)$ , are assumed to be members of a complete orthonormal set. Since this set of modes is complete, a modal expansion of any shape the mirror can take can be obtained by using the correct coefficient for each mode:

$$W(x,y,t) = \sum_{i=1}^{\infty} C_i(t)U_i(x,y)$$
(3)

Therefore, for any N points on the mirror, the following equation may be written symbolically in matrix format:

or

$$\dot{\mathbf{W}}^{\mathbf{N}} = \mathbf{U}^{\mathbf{N}}\mathbf{C}^{\mathbf{N}} + \mathbf{U}^{\mathbf{R}}\mathbf{C}^{\mathbf{R}} \tag{5}$$

where

$$\mathbf{U}^{\mathbf{R}}\mathbf{C}^{\mathbf{R}} = \begin{bmatrix} \mathbf{U}_{\mathbf{N}+\mathbf{1}}(\mathbf{x}_{\mathbf{1}},\mathbf{y}_{\mathbf{1}}) & \cdots & \mathbf{U}_{\mathbf{M}}(\mathbf{x}_{\mathbf{1}},\mathbf{y}_{\mathbf{1}}) & \cdots & \mathbf{C}_{\mathbf{N}+\mathbf{1}}(\mathbf{t}) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \mathbf{U}_{\mathbf{N}+\mathbf{1}}(\mathbf{x}_{\mathbf{N}},\mathbf{y}_{\mathbf{N}}) & \cdots & \mathbf{U}_{\mathbf{M}}(\mathbf{x}_{\mathbf{N}},\mathbf{y}_{\mathbf{N}}) & \cdots & \mathbf{C}_{\mathbf{M}}(\mathbf{t}) \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}}(\mathbf{t}) & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}}(\mathbf{t}) & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}}(\mathbf{t}) & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}}(\mathbf{t}) & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}}(\mathbf{t}) & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}}(\mathbf{t}) & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}}(\mathbf{t}) & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}}(\mathbf{t}) & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}}(\mathbf{t}) & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}}(\mathbf{t}) & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}}(\mathbf{t}) & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}}(\mathbf{t}) & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}}(\mathbf{t}) & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}}(\mathbf{t}) & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}}(\mathbf{t}) & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}}(\mathbf{t}) & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}}(\mathbf{t}) & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}}(\mathbf{t}) & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}}(\mathbf{t}) & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}}(\mathbf{t}) & \vdots & \vdots \\ \mathbf{C}_{\mathbf{M}$$

and UR is an Nx matrix and CR is an mx1 vector.

The second term in equation (5) causes an error when the mode amplitudes are determined since they are not available, and the amplitudes  $\, C^N \,$  are estimates denoted  $\, \hat{C}^N \,$ 

$$\hat{C}^{N} = [U^{N}]^{-1} W^{N} = C^{N} + [U^{N}]^{-1} U^{R} C^{R}$$
(7)

The term  $\left[U^{N}\right]^{-1}U^{R}C^{R}$  represents the error in the estimate of C. It is possible to take more measurements than the number of actuators used. If for example the number of measurements is selected to be M (M > N), then

$$\hat{C}^{M} = \left[ \mathbf{U}^{M} \right]^{-1} \mathbf{W}^{M} = \mathbf{C}^{M} + \boldsymbol{\xi}^{M} \tag{8}$$

where

$$\xi^{\mathbf{M}} = \begin{bmatrix} \mathbf{U}_{\mathbf{M+1}}(\mathbf{x}_{1}, \mathbf{y}_{1}) & \dots & \mathbf{C}_{\mathbf{M+1}}(\mathbf{t}) \\ \vdots & & & \vdots \\ \mathbf{U}_{\mathbf{M+1}}(\mathbf{x}_{N}, \mathbf{y}_{N}) & \dots & \mathbf{C}_{\mathbf{M+1}}(\mathbf{t}) \end{bmatrix}$$
(9)

If M is sufficiently large, then  $\xi^{M}$  will be negligible. Therefore, it will be assumed that

$$\xi^{M}=0$$

From figure 1, the following equation may be written (with the x,y,t notation dropped):

$$C^{N} = q^{N} + \Lambda^{N} H^{N} \alpha^{N}$$
 (10)

Since

$$\alpha^{N} = -\left[H^{N}\right]^{-1} D^{N} \hat{C}^{N} \tag{11}$$

and it is assumed that

$$C^{N} = \hat{C}^{N} \tag{12}$$

substituting equations (11) and (12) into equation (10) gives

$$C^{N} = Q^{N} - \Lambda^{N} H^{N} [H^{N}]^{-1} D^{N} C^{N}$$
(13)

or

$$\mathbf{C}^{\mathbf{N}} = \left[\mathbf{I} + \Lambda^{\mathbf{N}} \mathbf{D}^{\mathbf{N}}\right]^{-1} \mathbf{q}^{\mathbf{N}} \tag{14}$$

From the other path in the system model in figure 1,

$$C^{R} = \Lambda^{R} H^{R} \alpha^{N} + q^{R}$$
 (15)

Substituting equations (11) and (12) into equation (15) yields

$$C^{R} = -\Lambda^{R} H^{R} \left[ H^{N} \right]^{-1} D^{N} C^{N} + q^{R}$$
(16)

Substituting equation (14) into equation (16) to eliminate CN gives

$$C^{R} = -\Lambda^{R} H^{R} [H^{N}]^{-1} D^{N} [I + \Lambda^{N} D^{N}]^{-1} q^{N} + q^{R}$$
(17)

By inserting  $\left[\Lambda^N\right]^{-1}\Lambda^N$  into equation (17), the following expression for  $C^R$  is obtained:

$$C^{R} = -\Lambda^{R} H^{R} [H^{N}]^{-1} [\Lambda^{N}]^{-1} \Lambda^{N} D^{N} [I + \Lambda^{N} D^{N}]^{-1} q^{N} + q^{R}$$
(18)

Equations (14) and (18) give the dynamic values of the modal coefficients of the error in the mirror surface. In the present application it is anticipated that the primary errors will be the initial figuring errors and thermal gradients that vary relatively slowly with time. Therefore it is reasonable to expect that the system will be generally at or near its steady state. The steady-state performance of the system is discussed in the following section.

#### Evaluation of Steady-State Errors

In determining the steady-state performance of the entire system, first equation (14) will be used to assess the resulting error in the controlled modes and then equation (18)

will be used to determine the error in the remaining modes. Taking the Laplace transform of equation (14) and considering the disturbance vector q as a step input allows application of final-value theorem to determine the steady-state condition:

$$C_{SS}^{N} = \lim_{t \to \infty} C^{N}(t) = \lim_{s \to 0} sC^{N}(s) = \lim_{s \to 0} s \left[ I + \Lambda^{N} D^{N} \right]^{-1} \operatorname{col}\left(\frac{q_{i}}{s}\right) \qquad (i = 1, ..., N)$$
 (19)

The matrices  $\Lambda^N$  and  $D^N$  are both diagonal with

$$\Lambda^{N} = \operatorname{diag}\left[\frac{1}{s^{2} + \epsilon_{i}s + \omega_{i}^{2}}\right] \qquad (i = 1, \ldots, N; \epsilon > 0) \qquad (20)$$

where equation (20) assumes some structural damping.

The diagonal matrix  $D^N$  can be formulated at the discretion of the designer; however, a type 1 system is assumed, so that the combination of  $\Lambda^N$  and  $D^N$  is of the form

$$\Lambda^{N}D^{N} = \operatorname{diag} \left[ \frac{K(\tau_{1}s + 1) \dots (\tau_{n}s + 1)}{s(\tau_{1}'s + 1) \dots (\tau_{n}'s + 1)} \right]$$
(21)

and

$$\left[I + \Lambda^{N}D^{N}\right] = \operatorname{diag} \left[\frac{s \prod_{i=1}^{n} \left(\tau_{i}'s + 1\right) + K \prod_{i=1}^{n} \left(\tau_{i}s + 1\right)}{s \prod_{i=1}^{n} \left(\tau_{i}'s + 1\right)}\right]$$
(22)

which can be simplified to the form

$$\left[I + \Lambda^{N}D^{N}\right] = \operatorname{diag}\left[\frac{K \prod_{i=1}^{r+1} \left(\tau_{i} \text{''s} + 1\right)}{s \prod_{i=1}^{n} \left(\tau_{i} \text{'s} + 1\right)}\right]$$
(23)

by properly combining the numerator of equation (22) and factoring. Putting equation (23) into equation (19) and taking account of the inverse yields

$$C_{SS}^{N} = \lim_{s \to 0} \left\{ s \operatorname{diag} \left[ \frac{s \prod_{i=1}^{n} (\tau_{i}'s + 1)}{\sum_{i=1}^{n+1} (\tau_{i}''s + 1)} \operatorname{col} \left\{ \frac{q_{i}}{s} \right\} \right\} = 0 \qquad (i = 1, \ldots, N)$$

$$(24)$$

This is the expected result that a type 1 system will drive the error in the controlled modes to zero.

In anticipation of evaluating the steady state of equation (18), equation (21) and the inverse of equation (23) are combined to get

$$\lim_{s\to 0} \Lambda^{N} D^{N} \left[ \mathbf{I} + \Lambda^{N} D^{N} \right]^{-1} = \lim_{s\to 0} \operatorname{diag} \left[ \frac{K \prod_{i=1}^{n} \left( \tau_{i} \mathbf{s} + 1 \right)}{\mathbf{s} \prod_{i=1}^{n} \left( \tau_{i} \mathbf{s} + 1 \right)} \frac{\mathbf{s} \prod_{i=1}^{n} \left( \tau_{i} \mathbf{s} + 1 \right)}{\mathbf{s} \prod_{i=1}^{n+1} \left( \tau_{i} \mathbf{s} + 1 \right)} \right] = \mathbf{I}$$
(25)

Furthermore, since

$$\lim_{\varepsilon \to 0} \Lambda^{R} = \lim_{s \to 0} \operatorname{diag} \left[ \frac{1}{s^{2} + \epsilon_{i} s + \omega_{i}^{2}} \right] = \operatorname{diag} \left[ \frac{1}{\omega_{i}^{2}} \right]$$
 (26)

and

$$\lim_{s\to 0} \left[\Lambda^{N}\right]^{-1} = \lim_{s\to 0} \operatorname{diag} \left[\frac{1}{s^{2} + \epsilon_{i}s + \omega_{i}^{2}}\right]^{-1} = \operatorname{diag} \left[\omega_{i}^{2}\right]$$
 (27)

equation (25) can be used to determine the steady-state value of equation (18):

$$C_{ss}^{R} = \lim_{s \to 0} sC_{(s)}^{R} = -\Lambda^{R}H^{R}[H^{N}]^{-1}[\Lambda^{N}]^{-1}q^{N} + q^{R}$$
 (28)

or

$$C_{SS}^{R} = q^{R} - \Lambda^{R} H^{R} \left[ \Lambda^{N} H^{N} \right]^{-1} q^{N}$$
(29)

where equations (26) and (27) indicate the nature of  $\Lambda^R$  and  $\left[\Lambda^N\right]^{-1}$ . The nature of the H matrix and how to evaluate it is given in the next section. Equation (29) states that the final steady-state error consists of two parts. The first part  $(c^R)$  is that due to the original error in the R=M-N modes which were not controlled. The second part of the error is that generated by the control system itself as it corrects the error in the first N modes.

A few notes on the dimensionality of the matrices in equation (29) are in order. The error vector  $\mathbf{q}^N$  is the initial error in the N modes (not necessarily the first N) selected to be controlled and is N × 1;  $\mathbf{q}^R$  is the set of errors in the remaining modes and is R × 1. Therefore,

The  $\Lambda^N$  matrix is an  $N \times N$  diagonal matrix which consists of the natural frequencies of the modes being controlled;  $\Lambda^R$  is an  $(M-N)\times (M-N)$  diagonal matrix of the frequencies of the remaining modes. The  $H^N$  and  $H^R$  matrices are  $H^R$  $H^R$  matrices are

#### Determination of Pad Effects

The function of the H matrices  $(H^N)$  and  $H^R$  is to take the point loads of the actuators and transform them into modal coordinates. To determine the elements of the two H matrices, consider first the continuous case. Let the force distribution on the mirror P(x,y,t) be denoted by P

$$P = \sum_{i=1}^{N} \alpha_{j}(t) \beta_{j}(x,y)$$
 (31)

where  $\alpha_j(t)$  is the time-varying coefficient of the jth actuator and  $\beta_j(x,y)$  is the distribution of the force on the mirror because of the pad. A "pad" is the physical device that connects the actuator to the mirror. This force distribution may be expanded by using the complete orthonormal set of modes:

$$\beta_{j} = \sum_{i=1}^{\infty} h_{ij} U_{i}$$
 (32)

where the (x,y,t) notation is understood. Because of the properties of this set, the coefficients may be determined immediately:

$$h_{ij} = \int_{\Gamma} U_i \beta_j d\Gamma \tag{33}$$

where  $\Gamma$  is the area over which the pad acts.

Substituting equation (32) into equation (31) gives

$$P = \sum_{j=1}^{N} \alpha_j \sum_{i=1}^{\infty} h_{ij} U_i = \sum_{i=1}^{\infty} \left( \sum_{j=1}^{N} h_{ij} \alpha_j \right) U_i$$
(34)

Another way of writing equation (31) is

$$P = \sum_{i=1}^{\infty} a_i U_i \tag{35}$$

which expresses P directly in terms of the eigenvectors. The implication of equations (35) and (34) is that

$$a_{i} = \sum_{j=1}^{N} h_{ij} \alpha_{j}$$
 (36)

or

$$\left\{a\right\} = \left\{\frac{a^N}{a^R}\right\} = \left[\frac{H^N}{H^R}\right] \left\{\alpha^N\right\}$$

The elements of the H matrix are defined by equation (33). If small pads are assumed and it is further assumed that the load distribution is uniform, then

$$\beta_{j} = \frac{1}{\int_{\Gamma} dA}$$
 (37)

The assumption of small pads leads to the conclusion that the mode shape is relatively constant over the area of one pad, and equation (33) becomes

$$h_{ij} = \int_{\Gamma} U_{i} \beta_{j} d\Gamma = \beta_{j} \int_{\Gamma} U_{i} d\Gamma \approx \frac{U_{i}(x_{j}, y_{j}) \int_{\Gamma} dA}{\int_{\Gamma} dA}$$
(38)

and

$$\lim_{\Gamma \to 0} H = \begin{bmatrix} U_{1}(x_{1}, y_{1}) & U_{1}(x_{2}, y_{2}) & \dots & U_{1}(x_{N}, y_{N}) \\ U_{2}(x_{1}, y_{1}) & U_{2}(x_{2}, y_{2}) & \dots & U_{2}(x_{N}, y_{N}) \\ \vdots & & & & & \\ U_{M}(x_{1}, y_{1}) & U_{M}(x_{2}, y_{2}) & \dots & U_{M}(x_{N}, y_{N}) \end{bmatrix}$$
(39)

When selecting the terms  $U_i(x_j,y_j)$  in equation (39), the coordinates  $(x_j,y_j)$  are determined by the actuator locations since  $\beta_j$  is assumed zero everywhere except at the actuator location. Note that the H matrix is non-quare. There will be N columns corresponding to the N actuator locations used; however, all M rows will be present since each and every actuator will, in general, excite all M modes. For analysis purposes it is convenient to partition the H matrix into two parts:

$$H = \left[\frac{H^{N}}{H^{R}}\right] \tag{40}$$

The first matrix  $\mathbf{H}^{\mathbf{N}}$  consists of the  $\mathbf{N}$  rows which correspond to the modes which have been selected to be controlled by the  $\mathbf{N}$  actuators;  $\mathbf{H}^{\mathbf{N}}$  is therefore square. It is not necessary that the first  $\mathbf{N}$  rows ( $\mathbf{N}$  modes) be selected; however, this is usually desired. The reason for this will become clear in the examples. This arrangement will be assumed in future notation for the  $\mathbf{H}^{\mathbf{N}}$  matrix.

Since  $H^N$ ,  $H^R$ ,  $\Lambda^N$ ,  $\Lambda^R$ ,  $q^N$ , and  $q^R$  have now been obtained, the steady-state error from equation (29) may be calculated for a given choice of actuator locations and modes to be controlled. The only remaining consideration is the performance index.

### PERFORMANCE EVALUATION

#### Calculation of the Performance Index

To obtain the best performance from an optical system, it is necessary to minimize the rrs surface error of the elements (ref. 8). This error is defined as

$$J^* = \sqrt{\frac{1}{A} \int_A W^2(A) dA}$$
 (41)

For analysis purposes it is usually easier to work with a slightly different quantity which provides an equally valid measure of relative performance:

$$J = J^{*2} \tag{42}$$

Using J at the performance index and changing to discrete notation because of the numerical nature of the mirror problem gives

$$J = \frac{1}{A} \sum_{i=1}^{M} W_i^2 \Delta A_i \tag{43}$$

or, in matrix notation,

$$\mathbf{J} = \frac{1}{A} \mathbf{W}^{\mathbf{T}} [\Delta \mathbf{A}] \mathbf{W} \tag{44}$$

where

 $[\Delta A]$  diag  $[\Delta A_i]$ 

W M×1 vector of mirror displacements or errors

A total area

The first N modes will contribute no steady-state error to a step response in a type 1 system since it was assumed that  $\hat{\mathbf{C}}^N = \mathbf{C}^N$ . The final value of W is therefore given by

$$W = \begin{bmatrix} U \end{bmatrix} \begin{bmatrix} 0 \\ c_{ss} \end{bmatrix}$$
 (45)

where  $C_{SS}^R$  is the  $(M-N)\times 1$  or  $R\times 1$  vector of the final error in the uncontrolled modes and is obtained from equation (29). If U, the matrix of eigenvectors, is obtained from a finite-element program — as was done herein — then the eigenvector matrix is orthogonal with respect to the mass matrix m (refs. 4 and 5):

$$\mathbf{U}^{\mathbf{T}}\mathbf{m}\mathbf{U} = \mathbf{I}$$

For a homogeneous mirror of uniform thickness, m may be specified as an area associated with each grid point in the analysis times an area density constant  $\rho$ . Then m may be written as

$$m = \rho \operatorname{diag}[\Delta A_{i}] = \rho[\Delta A] \tag{46}$$

or

$$\frac{1}{\rho}[m] = [\Delta A] \tag{47}$$

Using equations (47) and (45) in equation (44) gives

$$J = \frac{1}{A} \begin{bmatrix} C_{SS}^R \end{bmatrix}^T U^T \frac{1}{\rho} \begin{bmatrix} m \end{bmatrix} U \begin{bmatrix} C_{SS}^R \end{bmatrix}$$
 (48)

$$J = \frac{1}{\rho A} \begin{bmatrix} c_{ss}^{12} \end{bmatrix}^{T} U^{T} \begin{bmatrix} m \end{bmatrix} U \begin{bmatrix} c_{ss}^{R} \end{bmatrix}$$
(49)

$$\mathbf{J} = \frac{1}{\rho \mathbf{A}} \begin{bmatrix} \mathbf{c}_{ss}^{\mathbf{R}} \end{bmatrix}^{\mathbf{T}} \begin{bmatrix} \mathbf{c}_{ss}^{\mathbf{R}} \end{bmatrix}$$
 (50)

$$\mathbf{J} = \frac{1}{m_t} \left[ \mathbf{C}_{ss}^{\mathbf{R}} \right]^{\mathbf{T}} \mathbf{C}_{ss}^{\mathbf{R}} = \frac{1}{\mathbf{A}} \mathbf{W}^{\mathbf{T}} \left[ \Delta \mathbf{A} \right] \mathbf{W}$$
 (51)

where the total mass is

$$m_{t} = \sum_{i=1}^{M} \Delta m_{i} \tag{52}$$

The contribution to the mean-square error of any mode is seen from equation (51) to be given by  $C_i^2/m_t$ .

In any approach where the controller is designed by use of an alternate representation of the mirror, it is important to express the desired system performance within the framework of the alternate reference frame. The significance of equation (51) is that it expresses the figure of merit of the system performance — rms error — as a very simple function of the amplitudes of the higher order modes. Thus, minimum rms surface error on the mirror is obtained by minimizing the sum of the squares of the amplitudes of the higher order modes. If only a relative measure of one actuator arrangement over another is of interest, the term  $1/m_{\rm t}$  may also be dropped since it is constant for any given mirror. This gives

$$\mathbf{J}_{1} = \left[\mathbf{C}_{SS}^{R}\right]^{T} \left[\mathbf{C}_{SS}^{R}\right] \tag{53}$$

#### Treatment of Initial Errors or Disturbances

The q vector obtained from equal, in (1) assumes that the error at each grid point on the mirror surface is known. When this is used in equation (29), the resulting design represents a deterministic treatment of the errors. While such a treatment of the errors will lead to minimum final error, the result can also lead to overoptimism on the part of the designer. Consider the following case.

Given a set of initial errors, the designer determines that a specific actuator at rangement will reduce the final error to an acceptable value. When the mirror is placed in orbit, it is highly likely that the errors will be different from those anticipated. As a result, the second term in equation (29) — the error generated by the control system — will change, possibly significantly. Consequently, the total error as given by equation (29) may now be unacceptable. It is concluded, therefore, that the "best" actuator location, based on deterministic errors, is sensitive to initial error. The question is, of course, how sensitive? Usually very sensitive, because the actuator positions have been chosen to generate specific amounts of error in the uncontrolled modes (generally opposite and equal to what was originally there) when specific amounts of error are removed in the controlled modes. A slight change in the error in the controlled modes, therefore, could make a great deal of difference in the final error.

An alternate way to treat an error is in an uncorrelated fashion, as suggested in reference 3. In this approach the values of  $C_{SS}^{R}$  are still given by equation (29); however, the performance index is now the expected value of the mean-square error

$$E(J) = \frac{1}{A} E \left[ W^{T} \Delta A W \right]$$
 (54)

where E is the expectation operator. If the errors are uncorrelated, then

$$\mathbf{E}(\mathbf{q}_{i}\mathbf{q}_{j}) = 0 \qquad (i \neq j) \tag{55}$$

and the performance index becomes

$$E(J) = E\left(\left[q^{R}\right]^{T}q^{R} + \left[q^{N}\right]^{T}\psi^{T}\psi_{q}N\right)$$
(56)

For the assumed type 1 system, where

$$\psi = \Lambda^{R} H^{R} \left[ \Lambda^{N} H^{N} \right]^{-1}$$
(57)

equation (56) may be rewritten as

$$E(J) = \sum_{i=N+1}^{M} c_{q_i}^2 + \sum_{j=1}^{M-N} \left( \sum_{i=1}^{N} \psi_{j,i}^2 \sigma_{q_i}^2 \right)$$
 (58)

where the variance of the error, which is assumed to have zero mean, is given by  $\sigma_{\bf q_i}^2$ . By reversing the order of summation in the second term of equation (58) and making the additional substitution

$$\phi_i^2 = \sum_{j=1}^{M-N} \psi_{j,i}^2 \tag{59}$$

equation (58) can be rewritten

$$E(J) = \sum_{i=N+1}^{M} \sigma_{q_i}^2 + \sum_{i=1}^{N} \phi_i^2 \sigma_{q_i}^2$$
 (60)

One notation addition is needed in equation (60), that is, to add the subscript N to E and to  $\phi_i^2$  to indicate the number of actuators being used. This will prevent confusion later. Equation (60) is then written

$$E_{N} = \sum_{i=N+1}^{M} \sigma_{q_{i}}^{2} + \sum_{i=1}^{N} \phi_{iN}^{2} \sigma_{q_{i}}^{2}$$
 (65)

It should be pointed out that equation (61) represents an expected error. Depending upon the inclination of a particular individual, he may choose  $J^*$ , J, or  $J_1$ , given by the previous equations, as a measure of the performance. The only problem with these equations for the performance is that they require exact knowledge of the error vector and may be quite sensitive to changes in the error vector, while equation (61) requires only a knowledge of the variance of the error. It is more realistic to make an engineering estimate of this latter quantity than of the actual errors.

In equation (61) both parts of the error are seen to be positive. This means that the two error components will add directly. To influence the expected error, the designer may do two things. First, he should encourage the opticians to keep the error in the higher order modes as small as possible because he cannot do anything to reduce this error except possibly increase the value of N. Second, he should select actuator locations which would minimize the value of  $\phi_{iN}^2$ . In fact, if  $\phi_{iN}^2$  could be made zero for  $i=1,\ldots,N$ , then the expected error would be independent of the initial error in the controlled modes. Since most of the error will likely occur in the first N modes, choosing actuator locations to minimize  $\phi_{iN}^2$  will lead to locations which tend to produce performance indices virtually independent of changes in error.

In the following sections and the appendixes, various design examples will be given which are based upon the theory developed up to this point. Effects of initial errors, actuator placement, error treatment, and the number of actuators necessary for a particular case will be discussed.

#### DESIGN PROCEDURE

# Numerical and Physical Data

The mirror which will be used in the analysis is shown in figure 2. It is a 1.27-cm-thick (1/2-inch), 76-cm-diameter (30-inch), F/3 spherical mirror which is supported on a kinematic (non-overconstrained) mount.

As mentioned in the Introduction, it is generally not possible to obtain closed-form expressions of the eigenfunctions of a practical mirror configuration such as that con-

Figure 8.- Photograph of To-ca-diameter (50-inch) deformable mirror which was modeled for this report.

sidered here. Therefore, estimates of the eigenfunctions are sought through numerical techniques. An analysis of the mirror was made with the SAMIS structural analysis program (ref. 4) and the grid breakup shown in figure 3(a). This grid breakup was adopted to comply with the SAMIS recommendation for use of equilateral triangles for maximum accuracy. This pattern also insured the location of a grid point (where forces may be applied and displacements censed) at each actuator and sensor location of the existing mirror shown in figure 2. The actuator and sensor locations are shown in figure 3(b), where the numbers refer to grid points. As reported in reference 7, this procedure provides a satisfactory clacrete model of the mirror behavior.

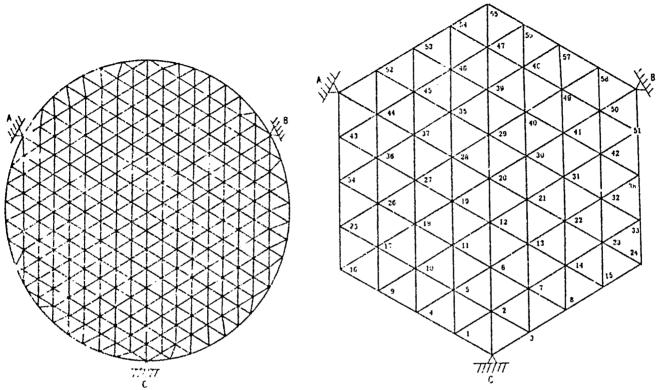
In the preceding sections, M has represented the finite number of modes used in new of the infinite number which would be required for an exact representation of the mirror. In performing a specific design it is desirable to select a value for M which is high crough to limit the error in the analysis and yet is not so high that it would require an excessive amount of calculation. Because of the inability to place a bound on the error incurred through the choice of a specific value of M, the choice is not subject to precise evaluation. In the present study the mirror shown in figure 2 was available for corroboration of theoretical results. This mirror has 58 displacement sensors, which similarly limit the maximum number of mode amplitudes that can be estimated. For this reason  $M \approx 58$  was selected for the present study. It is believed that this number is more than adequate for the present application; however, an exhaustive study on this point was not performed and it is possible that a smaller value of M might also be satisfactory.

The matrix of eigenvectors determined from this model to given in appendix B, and appendix C contains plots of node lines for a selected set of modes. The numbers on these plots are the value of the eigenvectors at the grid points. Therefore, each figure represents one eigenvector. The orientation of the figures in appendix C is the same as that in figure 3(b) to allow grid point numbers and eigenvalues to be correlated. The eigenvalues of the mirror are given in appendix D and are plotted in figure 4. For completeness appendix D also contains a listing of the diagonal mass matrix.

For design and analysis purposes three error vectors were assumed. The first error vector was obtained from reference 2 and is the error in figuring the mirror. The second and third were arbitrarily generated. The second was generated by assuming a set of four forces of 4.448 newtons (1 pound) located at grid points 16, 20, 21, and 40. The third example error was a parabolic error. The modul coefficients  $|q_1|$  for these three error examples are listed in table 1.

## Control System Design Evaluation

The basic design procedure consists of setting up a trial design, evaluating  $C_{bS}^{R}$  from equation (29), calculating  $J_{1}$  from equation (53), and comparing this value of  $J_{1}$ 



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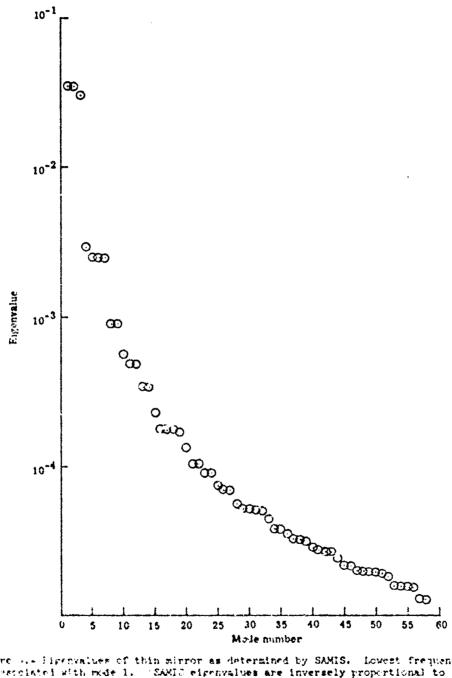


Figure ... Figenvalues of thin mirror as determined by SAMIS. Lowest frequency is aparchated with mode 1. "SAMIS eigenvalues are inversely proportional to frequence."

with previous or desired results. It the results are not satisfactory, then a new design is tried. Since many trials will be necessary, the only practical approach is to perform the design with the aid of a computer. A program to build the various matrices and to evaluate  $C_{SS}^R$  and the performance index  $J_1$  has been written in FORTRAN IV and is given in appendix A. The flow diagram for the program is given in figure 5, where the steps of the design procedure are set out in a straightforward manner.

As shown in figure 5, the program will first read in values of the eigenvector matrix, the eigenvalues, and the initial error, or disturbance, vector. The program must then be supplied with the number of actuators N to be used and the placement of these actuators. Actuator placement is specified by grid numbers. The selection of actuator location and number is the major degree of freedom that the control system designer has, and this selection more than any other will influence the value of  $J_1$ . The program must then be supplied with the number of modes to be controlled (the number of controlled modes must equal the number of actuators) and these modes identified. Identification of modes is by mode number corresponding to the column numbers of the U matrix. With minor exceptions, these should always be the first N modes. From this point the program will sort the  $\Lambda$ , q, and H matrices and carry out the calculation of  $C_{SS}^{R}$  and  $J_{1}$ . The program will also do one other task; namely, it will calculate the actuator forces and final error on the basis of making a least-squares fit of the errors to the desired chape. This allows a comparison of the modal control law to an optimal control law for the same actuator locations. One restriction on the program, and ultimately the designer's freedom, is that the choice of actuator placement must be restricted to grid points of the structural analysis model. Tris restriction has not been found to be serious in the present resuel, which has 58 grid points.

One particular word of caution is in order about this, or any other program, which is used to calculate the final error. For a given pad shape and size and a given set of modes to be controlled, selecting the actuator placement pattern fixes the H<sup>N</sup> matrix. Since the inverse of H<sup>N</sup> is part of the controller, the actuator locations must be chosen to insure that H<sup>N</sup> is nonsingular. A singular (or ill-conditioned) H<sup>N</sup> matrix indicates that the designer has placed actuators in such a manner that the amplitude of at least one controlled mode at these actuator locations is (or is nearly) a linear combination of the amplitudes of the other controlled modes. If H<sup>N</sup> is singular, the eccuators cannot independently control the giver modes. If H<sup>N</sup> is ill conditioned, the modes can be controlled but only at the expense of large applied control forces, which generate considerable error in the higher order modes. The designer obviously must avoid these cases; however, spotting a potentially singular matrix mainly on the 'asis of an actuator-placement pattern is almost impossible. The computer especially has trouble spotting this condition, since for reasons of numerical roundoff and the particular inversion procedure used, it will obtain "inverses" for very ill-conditioned or even singular matrices. The program given in

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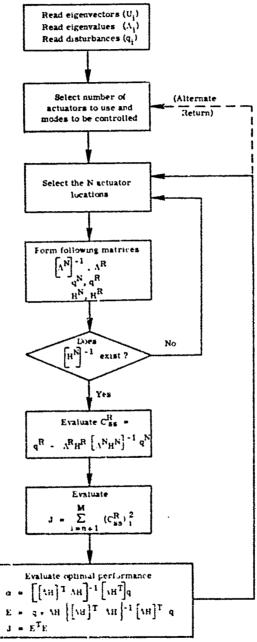


Figure 5.- Flow liagram of computer program in appendix A. This program evaluates the performance index for a given mirror and a given, or selected, set of actuator locations.

appendix A treats this problem by calculating and printing out the normalized determinant of  $H^N$ . If the normalized determinant is very small relative to 1.0, then  $H^N$  is said to be ill conditioned. (See ref. 9.) Usually an ill-conditioned  $H^N$  matrix will result in a large value of  $J_1$ , which automatically excludes that actuator arrangement. This, however, is not always the case. (See, e.g., fig. E10 and associated discussion.)

#### Results for Deterministic Errors

From the first set of errors a series of design trials were run with various numbers of actuators. For the 58-node mirror model, all possible combinations of one, two, three, four, and five actuators were surveyed. Beyond five actuators, the number of possible combinations becomes too large to make exhaustive searches. Several design "rules of thumb" were tried to choose actuator locations; however, none of these provided values of J1 that were considered to be near the minimum in light of the results from the exhaustive searches carried out for fewer actuators.

The technique that produced the best results was a gradient-type search which used the computer interactively. In this technique an initial actuator placement is chosen and the output of the computer is presented on a CRT. A perspective view of the mirror is also generated which shows the deformed state after control. A series of these perspective plots for five actuators is given in figure 6. On the basis of the tabulated data and the perspective plot, one actuator is moved one grid point and the program rerun to see whether a gradient can be set up on  $J_1$  to improve the mirror performance. At most, six trials are required to exhaust the possible moves for one actuator. The most important single piece of information turned out to be the perspective plot — especially early in the search procedure. This plot allowed the grid point with the largest error to be easily spotted, and the actuator nearest this error was moved. The series in figure 6 took approximately 2 hours and improved the performance index  $J_1$  from an initial value of 1136.6 to a value of 100, a factor of 10. Further effort beyond this point failed to provide improvement.

The results obtained from these gradient runs can be compared with the known minimum value  $J_1 = 72$ , obtained from an exhaustive search. The total number of runs that were required in the gradient-starch process was 63. If the program were implemented so that the computer made all the choices of actuator placement, the gradient search would require about 30 seconds of computer time. The use of the computer in the interactive mode, however, allowed considerably more insight to be gained into what factors were affecting performance and what factors were not.

The results of the exhaustive searches for up to five actuators are given in appendix E. In each case the best 10 locations are zhown. The initial performance index in all cases was  $J_1 = 1136.6$  and two "inal errors are given. The first is the final error

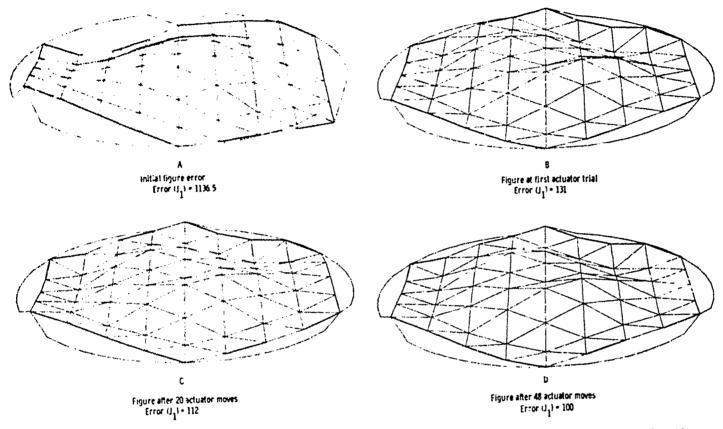


Figure 6.- Perspective views of the mirror at various stages during the gradient search for best actuator location - five-actuator case. The final diagram D is a local minimum, i.e., moving any one actuator one grid point will not improve the figure. Vertical scaling is variable for visibility purposes.)

obtained with the modal control law and the second is the result obtained when the actuator force is selected to minimize the rms error on the mirror. This is referred to herein as the optimal control law. A summary of these results in given in figure 7 for the modal control law. This figure shows the minimum error obtained plotted against the number of actuators used. The top curve is for the first error example and the lower curve is for the parabolic-error condition. Note that the rertical scale is logarithmic.

The plot in figure 7 suggests an empirical method of estimating the minimum number of actuators that a particular disturbance vector might require for a given mirror and performance index. That is, an exhaustive search over the model is made for a limited number of actuators and the results extrapolated to the desired performance. This would, of course, be equivalent to assuming an exponential decay of error with increasing number of actuators. The class of errors and plants for which such an assumption would hold is not known. Clearly, the error generated by the four loads of 4.448 newtons (1 pound) at the discrete grid points is not in this class since the final error is zero for four or more properly located actuaiors.

The problem with the deterministic approach is that first, there is presently no way to determine readily the best actuator placement, and second, the placement is very sensitive to initial error.

#### Results for Uncorrelated Errors

When the designer assumes uncorrelated errors, considerably more can be said about where actuators should be placed and how many actuators will be needed.

First, equation (61) is minimized instead of equation (29). Since the first term in equation (61) is constant for a particular number of actuators, the goal is to minimize the second term, which is the error generated in the uncontrolled modes by the control system. Instead of writing a program to do this, an alternative procedure which enabled the existing computer program to be used was adopted. This procedure yielded results that closely approximated those which would be obtained from equation (61). The alternate procedure consisted of a deterministic minimization of the second term in equation (29). This corresponds to the intent of the uncorrelated case in eliminating the possibility of a control-system-generated error canceling an existing error. If the values of  $\phi_{\rm iN}^2$  are sufficiently small, there will only be a trivial difference in performance between the two procedures. Since the second term of equation (61) is to be assumed small, the final value of the expected error is the first term of equation (61). A plot of this portion of the equation is given in figure 8.

Since the actuator locations are less sensitive to initial error for this criterion, exhaustive searches were run for only the first error example. The results of these searches are given in appendix F for one, two, three, and four actuators. The values of

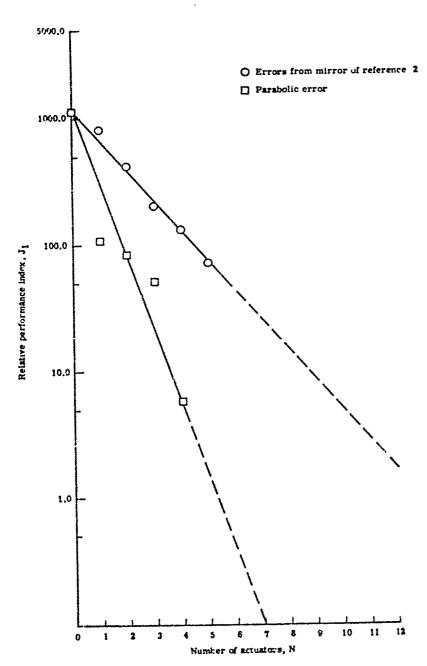


Figure 7.- Frror decay as a function of number of actuators for deterministic errors.

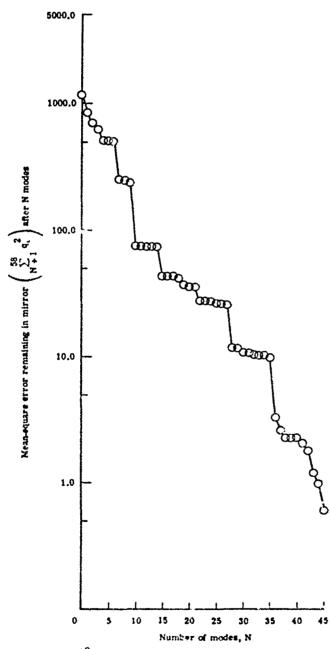


Figure 5.- Mean-square error  $\sum_{i=N+1}^{58} q_i^2 \text{ after N controlled modes. This plot indicates}$  expected terformance with N actuators, assuming uncorrelated errors. (Mode errors were taken from mirror of ref. 2.)

 $\phi_{1N}^2$  for the best run of each number of actuators are given in table II. Since the values of  $\phi_{1N}^2$  are relatively small, the expected error falls right on the predicted values of figure 8.

The choice of possible actuator locations can be considerably reduced when it is desired to minimize the generated error. A look at the actuator location for four actuators shows that each set lies very close to the node lines of mode 5 and several higher modes. As pointed out in reference 3, this means that these modes will not be excited to any great extent. The first mode that is excited to any great extent by this arrangement of four actuators is mode 11. The ratio of eigenvalues for mode 11 to mode 4 is

$$\frac{\Lambda_{11}}{\Lambda_4} = \frac{4.52 \times 10^{-4}}{2.95 \times 10^{-3}} = 0.166 \tag{62}$$

This means that the filtering action by the mirror is about 6 times as much for mcde 11 as for mode 4, the last controlled mode.

To test the concept of placing actuators at, or near, nodes of higher order modes to minimize the generated error, the case for seven actuators was tried. The sevenactuator case was chosen because of two factors. First the eigenvalue plot of figure 4 shows a distinct jump between modes 7 and 8. This implies good filtering action by the mirror at this point. Second, the expected-error plot of figure 8 shows a jump between six and seven actuators. This implies that a considerable increase in performance can be obtained with seven actuators over six actuators. In selecting the actual grid locations the node lines for modes 8, 9, and 10 were overlaid and a set of grid points near the junction of these modes was selected. (See the last diagram of tig. F5 in appendix F.) This reduced set of grid points was searched for those locations which yielded minimum generated error. The results of this search are given in table II  $(c_{ij}^2)$  and in the last set of figures of appendix F (actuator locations). The expected performance index with the best arrangement of seven actuators, obtained by using the minimum generated-error criterion, was  $J_1 = 274.9$ . Had all the values of  $\sigma_{17}^2$  been exactly zero, the performance index would have been  $J_1 = 250.6$ . The results, therefore, are very close to the predicted values of figure 8.

It should be noted that this result was obtained by searching only a relative few of the possible ectuator locations, therefore, it cannot be said that the result represents the actual minimum. The important point is that a relatively short computer run was able to establish a set of actuator locations having a final error very close to the absolute minimum.

Ľ

# Comparison of Modal Control and Optimal Control Laws

As was stated earlier the computer program which was used to calculate the final errors also calculated the error that would have been obtained if an optimal control law (least-squares fit to best sphere) had been used. In the modal domain the error is given by merging equations (10) and (15) to get

$$C = \frac{CN}{CR} = \frac{qN}{qR} + \frac{\Lambda N_H N}{\Lambda R_H R} \alpha^N$$

$$C = q + \Lambda H \alpha \tag{63}$$

It is desired to find the value of a which minimizes

$$\mathbf{J_1} = \mathbf{C}^{\mathrm{T}}\mathbf{C} \tag{64}$$

Therefore,

$$\frac{\partial J_1}{\partial \alpha} = 2[\Lambda H]^T [\Lambda I \bar{I}] \alpha + 2[\Lambda H]^T q$$
 (65)

This yields

$$\alpha = -\left[\left[\Lambda H\right]^{T} \Lambda H\right]^{-1} \left[\left[\Lambda H\right]^{T} q$$
(66)

From equation (66) the value of the forces needed to minimize the value of  $J_1$  is calculated. The vector C is then calculated from equation (63), and  $J_1$  is determined from equation (64). The computer program outputs the  $\alpha$  vector and the value of  $J_1$ . This can then be compared with the similar value of  $J_1$  under the modal control law,

Numerical comparisons are given in appendixes E and F. Generally, given a set of actuator locations that were "good," there was little difference in the final result. The counterbalancing features of these two control laws are that the modal control law enables the dynamic behavior of the mirror to be considered while the optimal control law would never make the mirror worse than it was originally. To create more error than the original error would require a rather gross misplacement of actuators on the part of the control-system designer; however, it is possible.

For example, when the errors of example 2 in table I are treated deterministically, the conclusion is that the best actuator location is in the center of the mirror. If now the

error distribution changes so that the mode I error and the mode 3 error are interchanged, the final error will be much worse than the original.

The reason for this is that the actuator was placed on a node of mode 1 while instructed to control mode 1. This produces considerable force, which generates considerable error. In the original distribution it was desirable to generate a lot of extraneous mode 3 error, but in the modified error distribution it is not desirable to generate much mode 3 error. The optimal control iaw, faced with the same situation, would do almost nothing in the second case, resulting in almost no change of figure error. For either control law the actuator placement was bad.

It should be recognized that any closed-loop control law, except one that has a decision-making capability as to relative performance, could result in a mirror figure that is worse than the original figure if the actuators are placed in a poor location. The ability of the modal control law to "order," or to establish a hierarchy of, likely mirror deformations through the eigenvectors and to provide a measure of relative likelihood through the ratio of eigenvalues means that the control-system designer will not place actuators in a bad location when using this control law.

### Design Examples

To be specific, consider the case for four actuators and error example 1. Trial actuator locations are grid points 2, 30,  $\ell$ 2, and 45; and the controlled modes are to be modes 1 to 4 inclusive. The  $H^N$  matrix is therefore given by

$$H^{N} = \begin{bmatrix} -1.092 \times 10^{-2} & 9.997 \times 10^{-3} & -1.307 \times 10^{-3} & 3.009 \times 10^{-2} \\ 5.199 \times 10^{-3} & 7.287 \times 10^{-3} & 3.454 \times 10^{-2} & -1.616 \times 10^{-2} \\ -2.278 \times 10^{-2} & -4.529 \times 10^{-2} & -3.302 \times 10^{-2} & -3.347 \times 10^{-2} \\ -1.453 \times 10^{-2} & -5.481 \times 10^{-2} & -1.235 \times 10^{-2} & -1.229 \times 10^{-2} \end{bmatrix}$$
(67)

The following information is then obtained from the computer program for this case:

- (i) The normalized determinant of HN is 0.23, which is considered satisfactory.
- (2) The force vector a is col[-2.108, 5.916, -3.256, 3.78] newtons (col[-0.471, 1.33, -0.732, 0.850] b), given in the same order as the actuator grid locations.

The remaining important results are tabulated below in both their relative values  $(J_1)$ , as determined by the program in appendix  $\Lambda$ , and their absolute values  $(J^*)$  as given by equation (41).

	Relative values	Absolute values (rms wavelength, λ, 0.6328 μm)
Total original error	1136.6	0.64
Original error in first four modes	618.0	0.474
Original error in remaining 54 modes	518.0	0.433
Error generated by the control system in the		
54 uncontrolled modes	346.0	0.354
Final error by the modal control law	131 1	0.218
Final error by the optimal control law ,	130.4	0.217

The results correspond to the best possible location for four actuators for the deterministic error criterion and error example 1.

For the case just given, all factors worked tog them oproduce an acceptable design; however, it is instructive to consider briefly a case that does not produce good results. For example, it was stated earlier that the first (lowest). No modes were usually controlled. Now consider a case in which this is not true. In error example 1, table 1, it can be seen that the four modes which contain most of the error are modes 1, 2, 7, and 10. Suppose that the above actuator locations (2, 30, 42, and 45) are used and the control system is designed to drive these four modes to zero instead of the first four. The H<sup>N</sup> matrix would now be different. For reference, the first column would now be

$$col\{-1.092 \times 10^{-2} \quad 0.519 \times 10^{-2} \quad -0.007 \times 10^{-2} \quad 5.809 \times 10^{-2}\}$$

This, in it:elf, presents no problems; however, in equation (62) the ratio of the eigenvalue of the first mode which would be excited  $\Lambda_{11}$  to the eigenvalue of the highest controlled mode  $\Lambda_4$  was

$$\frac{\Lambda_{11}}{\Lambda_4} = 0.166 < 1$$

which results in an attenuation of the control-system-generated error. For the case in which the four modes containing the most error are controlled, the ratio

$$\frac{\Lambda_3}{\Lambda_{10}} = \frac{3.06 \times 10^{-2}}{5.62 \times 10^{-4}} = 54 \tag{68}$$

results in an amplification of the control-system-generated error. One might therefore expect that the final error for controlling modes 1, 2, 7 and 10 could be worse than the error for controlling modes 1, 2, 3, and 4. The actual calculated final error for controlling modes 1, 2, 7, and 10 was found to be

$$J_1 = 1.83 \times 10^5$$

which is worse than the original error. It might be argued that a different actuator placement would improve this answer. Although this is probably true to some extent, a new set of actuator locations can only change the  $\mathbb{H}^N$  matrix but not the atio in equation (88), which is the underlying cause of the problem.

#### CONCLUDING REMARKS

A design procedure for selecting actuator locations on thin mirrors which are to be controlled by a modal control law has been worked out for use with typical numerical data. Instructions are given for constructing mathematical models of the system. Two ways of treating disturbances are discussed. These two techniques, deterministic and uncorrelated, are examined from the standpoint of sensitivity to various mirror errors, determining the number of actuators required, and means of finding the best locations. For the deterministic case it was found that the "best" actuator locations (those locations which will minimize the error) are very sensitive to the error distribution; these locations can presently be found only by exhaustive searches of all possible actuator locations, and the number of actuators required for a specific mirror and specific error can only be estimated after much computer time is used. For these reasons it is not recommended that errors be treated deterministically because the exact nature of the final figure-error distribution on the mirror surface will enange with telescope attitude.

When the errors are treated as if they are uncorrelated, the locations are much less sensitive to variations in error distribution, an estimate of the number of actuators required to produce a desired reduction in figure error can easily be made, and locations which will yield results near these estimates can be found in a reasonable manner. At present, this technique is much preferred even though it requires more actuators than the deterministic method for a specific assumed error.

For example, the deterministic case for five actuators and 58 possible locations requires  $4.6 \times 10^6$  trials. When the errors are treated as uncorrelated variables, however, it is possible to select a subset of the 58 grid points which will yield results close to the theoretical limit. This subset is chosen by selecting potential locations near the common node lines of the next few higher modes and making an exhaustive search of these

locations. Also, for the uncorrelated treatment it is possible to estimate the number of actuators a given mirror and mount configuration will require by using an estimate of only the variance of the expected errors.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., November 11, 1972.

## APPENDIX A

## COMPUTER PROGRAM DESCRIPTION, LISTING, AND PRINTOUT

This appendix contains a listing of the program to calculate figure error of the mirror on the basis of a type 1 modal controller which controls. No modes. The program contains a great deal of comment statements to aid the user, but a few additional comments are in order.

First, one must obtain a set of eigenvalues and the eigenvectors for the particular mirror to be analyzed. This is a major undertaking and should be done with a standard structural analysis program. The size of the eigenvector matrix is a critical item. Since actuators can be placed only at grid points of the structural analysis model, a sufficient number of these grid points must be used to allow reasonable flexibility in actuator placement. Too many grid points will result in a matrix that is too large to handle and requires excessive storage. The 58 grid points and the 58 × 58. U matrix used in this analysis have proved to be reasonable. This results in a storage requirement of 110 0008, which may be too large for some systems.

The next requirement is to chain an error vector. This may be obtained from experimental data by estimating or determining the mirror error at each grid point and multiplying by  $\begin{bmatrix} U \end{bmatrix}^{-1}$ , or it may be artificially generated, as were examples 2 and 3. In any case the program assumes that the error vector is already in modal coordinates. An option of multiplying this error vector by a constant (to change units) is provided also.

The next op ion selects the output. The short option is recommended for all runs except debogging and examining final runs. An example of the complete output is given after the program listing. The short option is the last page of output.

The final option allows the designer to change a few of the actuators and control modes without completely rewriting the data cards. By setting NEW = 1, a single actuator location (or several locations) can be shifted by one number. For example, if a set of seven actuators is being run and it is desired to vary the location of one or two actuators to several selected points on the mirror, it can be done by using this option. Assume that the original data cards contain modes 1, 2, 3, 4, 5, 6, and 7 as controlled modes and actuator locations of 6, 16, 20, 24, 38, 55, and 50, and it is desired to change an actuator location from grid point 50 to grid point 49. In this case the MOCHNGE would be zero and LOCHNGE would be 1, and the next card would centain the number 49 in proper format. The controlled modes would then be the same, but the actuator locations would be 6, 16, 20, 24, 38, 55, and 49. Note that it is necessary to place the actuator(s) to be moved at the end of the list in the original data card.

# APPENDIX A - Continued

The remainder of the program sorts matrices, calculates the various quantities needed to evaluate the performance, and formats the output. One point near the end of the program might cause confusion if data on a different mirror are used, that is, the conversion of the force vectors to pounds. The value of  $1.25 \times 10^{-9}$  assumed that the original errors on the mirror surface were in fringes ( $\lambda = 0.6328~\mu m$ ). If not, the error can be scaled in the first part of the program. Another potential trouble source is in the use of the eigenvalues. SAMIS eigenvalues are inversely proportional to frequency squared, and other programs (NASTRAN) output eigenvalues in frequency directly. This can be corrected at line 000467 by changing OMEGASQ(J) = 10000./LAMBDA(I) to OMEGASQ(J) = 10000.\*\* (frequency squared).

```
PROGRAM ACTUATE (INPUT, OUTPUT, TAPELO)
000003
               REAL LAMBCA(58)
               INTEGER UNCUCISAL OLCCAT(58)
000000
              DIMENSION ULSB.58), MUDC(58), LUCAT(58). DMEGASU(53), UINVDE(58).
000003
              1 HN(58,58), HR(58,58), CN(58), QK(58), HDLD(38,58)
              DIMENSION DUMMY(58,1), IPIVOT(58), INGEX(58,2)
000003
               CIMENSICH PHOD (58,581, PROD2 (58),
C00C03
              DIMENSION HOLDUP(58,58)
000003
               CIMENSICH ADIVIDE(58)
000003
              DIMENSIUM ARRAY(58,581, VECTOR(56)
000003
000003
               DIFLASION
                          ALPHA(58). ALPSTUR(58)
                            PHI (30) . L/ BEL (8)
               DIFERSION
GG0003
000003
               DIMENSION
                          UINVFLX(58)
               M = i)
000003
6000004
               N5E = 58
              READ IN THE U (EIGENVECTUR) AFFIX. THE LIGHNVECTURS ARE CULUMNS
               OF THE MATRIX.
000005
               DO 5 J=1.58
000007
               READ (10) (U(I,J),1=1,58 )
             5 CUNTINUE
000022
              READ IN THE CURRESPONDING EIGENVALUES.
        Ç
               REAC 203. LAPUCA
000024
000032
               PRINT 204, LAMBCA
              READ IN A DESCRIPTIVE HEADING FUR THE ERRUR VECTOR.
        L
               REAC 209. LABEL
000040
               PRINT 260, LABEL
000046
               READ IN ERROR VECTOR AND THE SCALER MULTIPLIER.
        C
0J0054
               REAC 203, UINVOE
               PRINT 205. UINVUE
000062
               READ 261, FACTOR
000070
               SCALE THE DEFLECTION VECTOR.
         €
000076
               DO 403 1=1,58
```

```
UINVOELD = UINVOELD + FACTOR
000100
000102
          403 CUNTINUE
              PRINT 262, FACTUR, UINVOS
J00104
              READ IN IPRINT. IF IPRINT = 0 PRINTOUT, WILL BE ABBREVIATED TO ONE PAGE
         C
              PER RUN. OTHERHISE PRINTOUT WILL INCLUDE SEVERAL INTERMEDIATE MATRICES.
                     206: IPRINT
000113
               READ
               NUMBUN IS THE NUMBER OF RUNS TO BE MADE. EACH ONE INVOLVES A
               DISTINCT SET OF MODES CONTROLLED AND ACTUATOR LOCATIONS.
000121
              REAC 206, NUMRUNS
         C
               BEGIANING OF DO-LOOP WHICH PROCESSES EACH RUN.
050127
               DG 350 IRUNS×1.MUMQUNS
         C
               REAC IN NEW. IF NEW = 1. A NEW SET OF MODES AND ACT. LOCATIONS IS READ IN.
         C
000131
               REAG 206. NEW
000136
               IF (NEW . EQ. 1) GG TC 415
               IF NEW .NE. 1, READ IN THE FULLOWING TWO VALUES WHICH INDICATE THE NUMBER
         C
               OF MODES AND ACT. LOCATIONS TO BE CHANGED.
         C
000140
               READ 206, MOCHNGE, LCCHNGE
000150
               IF (FCCHNGE-EQ. 0) CC TO 405
               MOCHNGE * MODE + 1 - MOCHNGE
000151
         C
         C
               REPLACE THE LAST MOCHINGE MICE NUMBERS WITH THE FULLUMING-
               READ 206, (CHODCIII, I=HUCHNGE, MODE)
C00133
030166
           405 IF (LCCHNGE .EQ. 0 ) GO YO 420
               LUCHNGE = NACT + 1 - LUCHNGE
030167
         Ĺ.
               REPLACE THE LAST LUCHNGE ACT. LOCATIONS WITH THE FULLOWING-
         C
000171
               READ 206, (ULOCAT(I), I=LCCHNGE, NACT )
CUUZ 04
               GC TO 420
               REAC IN AN ENTIRE NEW SEY OF MODES AND ACT. LUCATIONS.
```

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```
000205
          415 READ 200, MODE, (OMCCCII), I*1, MODE I
000222
              READ 206. (ULUCAT(I), I=1. MJUE)
030235
               NACT = MUDE
           420 CO 422 J=1.MUDE
000237
030241
              ACDC(I) = UMCOC(I)
000243
              LUCAT(I) * OLUCAT(I)
000244
          422 CCATINUE
000246
               IF INCUE .EQ. 11 GU TC 9
              THE FULLOWING LOOPS SORT THE MUDES AND ACTUATUR LUCATIONS IN ASCENDING
             GROER.
000250
              LIMIT = MODE - 1
000251
              OC 8 I=1. LIMIT
000252
              18EGIN = 1 + 1
000254
              OG 6 JJ=18EGIN. MCDE
000256
              IF (NGOC(I) .LT. MODC(JJ) ) GO TO &
000251
              IHOLD * MODCIII
240263
              MEDCITI * MECLETIF
UJU265
              MULCEUJ) = IFGED
            6 CENTIMUE
000255
030271
              JO 7 JJ=IEEGIN, NACT
030273
               IF (ELCATTI) .LT. LUCATTIJI) I GO TO 7
000276
               IHOLD . LOCATIII
000300
              LCCATILL . LUCATILLE
000302
              LOCATIJJI * INGLO
000303
            7 CUNTINUE
            8 CUNTINUE
C00303
030313
             9 IF (IFRINT .EC. 0 ) GG TO 15
030311
              PRINT 237, MODE, (MOCC(J),J=1,MODE)
000326
              PRINT 208, ILUCAT(I), I*I, NACT 1
000341
           15 MKINLSN= 58 - NACT
             CONSTRUCT THE HN AND HR PARTITIONS OF THE EIGENVECTUR MATRIX.
030343
               11 = 1
000344
              NHN = 1
000345
              AHR = 1
000346
              DO 4C I=1,58
               IF (1 .EJ. MODC(111)) 20,30
9G0350
000354
            20 11* 11 + 1
000356
               IF (II .GT. MODE) MODC(III)=0
              00 25 J=1.NACT
000361
```

...

1:5,

```
000363
               MULE . LOCAT!!!
000365
               HN(NHA+J) = U(MOLD+I)
000373
            25 CGNTINUE
C0C375
               NHA # AHN + 1
000376
               60 TC 40
000377
            30 CG 35 J=1, NACT
030401
               MOLE - LOCATEJS
000403
               HRIAFR.JI = U(MULD.I)
G00411
            35 CONTINUE
000413
               MHR # MHR +1
000414
            40 CONTINUE
000416
               IF (IPRINT .EQ. 0 ) GO TO 50
000417
               PRINT 210
000423
               DO 45 1-1. NACT
               PRINT 211, (HN(I,J), J=1, NACT)
000425
            45 CONTINUE
000441
         C
         C
              NOW. PARTITION Q BY THE HUDES CONTROLLED.
         C
G0C444
            50 II * 1
000445
               NR = 1
000446
               DU 60 I=1.58
000450
               IF (I .EQ. MGDC(III)) 52,54
000454
            52 CHILL = UINVOELLE
000457
               CHEGASO(II) = 10000./LAHBOA(I)
000461
               II = II + 1
000462
               60 10 60
000463
            54 GRINE) - UINVOEIII
000466
               J # MUCE + NR
000467
               OMEGASO(J) # 10000./LAMBOA(I)
030471
               NR = NR + 1
000473
            60 CONTINUE
000475
               IF LIPRINT .EQ. 0 1 CO TO 61
000476
               PRINT 213. (CH(1), I=1, NACT)
         C
              STORE MATRIX HN IN HOLD AND THEN INVERT IT.
000511
            61 DO 65 J=I,MUDE
000513
               DO 65 I=1-NACT
000514
               HOLD[I:J] = HN(I:J)
000523
            65 CONTINUE
000530
               CALL PATING (HN, NACT, DUMMY, M, DETERM, IPIGOT, INDEX, N58,
              1 ISCALE 1
```

1 . 25 . 24

```
IF (ISCALE .EC. 0) GC TU 66
000540
000541
               PRINT 231
               GG TC 350
000545
              PRIXIS OUT HN INVERSE.
J00546
           66 IF (IPRINT .EQ. 0 ) GO TC 675
000547
               PRINT 218
000553
               DO 67 1=1.NACT
000555
               PRINT 211. (HN(I,J),J = 1, MGDE)
000571
           67 CONTINUE
         C
        C
              NORMALIZE THE DETERMINANT OF HN.
000574
          675 CIV = 1.
000576
               00 76 I=1.MODE
               ADIVIDEII) = 0.
000577
000600
               DO 68 J#1. MACT
000602
               ADIVIDE(I) * ACIVIDE(I) + HCLC(I,J)**2
000510
            68 CONTINUE
               ADIVICE(I) = SCRT(ADIVICE(I))
000612
               DIV - DIV + ADIVIDE: II
000617
000621
            TO CONTINUE
000623
               DNERMAL . DETERM / DIV
              CHECK THE INVERSION ROUTINE BY RE-MULTIPLYING
000625
               CO 72 J=1,MGDE
               DO 72 I-1, NACT
000627
               PRCD(1.4) = 0.0
000630
000633
               DO 72 K=1.HODE
000635
               PROC(I,J) = PRUD(I,J) + HCLD(I,K) + HN(K,J)
000647
            72 CONTINUE
000656
               IF (IFRINT .EG. Q ) GD TU 735
000457
               PRINT 219
000663
               DU 73 I=1, NACT
               PRINT 211, (PROD(I, J), J=1, MODE)
000665
000701
            73 CONTINUE
         Č
               CALCULATE THE ALPHA VECTUR UNDER THE MCDAL CONTROL LAW.
C00704
           735 DO /40 I=1.NACT
000706
               ALPHACIS = 0.0
```

```
OCC7C7
               DO 74 J=1.MODE
000711
               ALPHP(1) = ALPHA(1) + FA(1, J' * OMEGASC(J) * QA(J)
000721
            74 CONTINUE
000723
           740 ALPSTOR(1) = ALPHA(1)
633730
               ATAN . D.
030731
               DO 140 I*1.NACT
               ATAN # ATAN + ALPHALII**2
000732
000735
           140 CONTINUE
630737
               ATAP - SURTERTAM)
         C
         Č
               CALCULATE THE ALPHA VECTOR UNDER THE OPTIMAL CONTROL LAW.
         C
               COMPLTE ( {LAF+H}TR + (LAH+H) }-1 + (LAM+H)TR + Q
CCC741
               DC
                     150
                           I=1. MMINUSN
030742
               DΩ
                     150
                           J=1. NACT
000743
               MGLD # I + MGDE
300745
               HGLC(FGLU,J) + HR(I,J)
020752
           ISO CONTINUE
               DQ 156 I=1.58
000757
300750
                          J=1, NACT
               CO 155
OCC761
               HOLDII-J) = HOLDII, JI/ CMEGASQII)
000767
           155 CONTINUE
000771
           156 CENTINUE
000773
               [F
                   (1PRINT .EC. 0 ) GO TO 157
000774
               PRINT 257
               PRINT 202, (HOLD(I,J), J=1, NACT )
000777
         C
         C
               INVEST THE MATRIX, AND NORMALIZE ITS DETERMINANT IN THE CALCULATION
               CF 2. PHA.
031014
           157 DIV * 1.
001016
                    : 69
                           I = 1.NACT
               Du 
031517
               ACIVITETI) # 0.0
001020
               CO
                   167
                           J= 1, NACT
001022
               ARRAY([.]) = 0.0
021025
                           K# 1.58
                   165
031027
               A"RAY(1,1) = ARRAY(1,1) + HCLD(K,1)+HGLD(K,1)
031041
           165 CONTINUE
001043
               ADIVIGE(1) = ADIVIDE(1) + ARRAY(1, 1)**2
001046
           167 CONTINUE
               ADIVICE(II) - SUNTIACIVIDE(III
001051
031055
               DIV # CIV * ACIVIDE(I)
UJ1057
           169 CUNTINUE
```

```
CALL MATING IARRAY, MACT, COMMY, H. DETERM, IPIVOT, INDEX. MSB.
031361
              1 ISCALE 1
               DETERMN * DETERM / DIV
331072
                  CIPRINT .EQ. O F GU TO 175
G31074
               PRINT 247. DETERM. ISCALE, DETERMN
001075
              PRINT OUT THE INVERSE OF ( (LAMPH)T * (LAMPH) )
         C
         c
031107
               FRINT 258
               DO 171 1=1. NACT
031113
               PRINT 202. (ARRAY(I.J).J.1.HACT )
001115
           171 CONTINUE
031131
         C.
031134
           175 00
                     180
                           J= 1.MUDE
               VECTOR(J) # CM(J)
G01136
001140
           180 CONTINUE
               MGLD . I + MCDE
031142
031143
                    155
                          Ja MOLD. 58
               VECTORIJI - CRIJ-HODE)
031144
021147
           185 CONTINUE
               S
                            I =1.HACT
031151
                     153
               ALPHALIS # 0.0
001153
               CO 193 J=1.58
JJ1154
               PROE(1.J) . 0.C
CJ1256
031161
                     193
                            K = I.NACT
               PROCELLUL = PROCELLUL + ARRAYLLIK) = HOLDEJIKO
001163
           190 CUNTINUE
001176
               ALPIZ(1) * ALPHA(1) * PROCITION * VECTOR(1)
001200
J31206
           193 CONTINUE
               ALPHSLY . U.O
001212
               DU 194 1=1.NACT
JJ1213
               ALPHALM # ALPHAUM # ALPHAUIT**2
031214
631217
           194 CONTINUE
               ALPESLA . SCRTTALPHSUM!
031221
              NUM CAICLLATE E TRANSPUSE E
031223
               00 155 1=1.58
               VECTURIII - 0.0
001224
               JU 195 J#1.MACT
031225
```

8

```
VECTORII) = VECTORIII + HCLDII, J) + ALPHAIJ)
001:21
051230
           195 CUNTINUE
               DO 156 1*1, MODE
001242
031244
               VECTOR(I) = VECTOR(I) - CN(I)
           196 CUNTINUE
031245
001250
               DG 197 I=1.MMINUSN
031252
               J - MODE + I
031254
               VECTOR(J) = VECTOR(J) - QR(I)
001256
           197 CONTINUE
001260
               5U# # 0.0
               00 158 1-1.58
001261
               SUF * SUM + VECTORIII**2
031262
001265
           198 CONTINUE
               ETE . SORT(SUN)
001266
         C
               CALCULATE PROD. THE MATRIX PRODUCT --
         Ç
               LAMEGAIRS * HIRS * HIRS INVERSE * LAMBDAIRS INVERSE. THE MULTIPLICATION
               IS SIMPLIFIED RECAUSE THE LAMBDA MATRICES ARE DIAGONAL.
001271
               ĐO
                   80 J* 1. MODE
031272
               DC BO IA L. MMINUSN
001273
               PRODULIJI = C.O
               CG 75 K=1. MUDE
031276
001303
               PROC(l, s) = PFOO(l, j) + MR(l, k)* HN(k, j)
001312
            75 CONTINUE
001314
               PRCD(I+J) = PFOD(I,J) = CMEGASQ(J) / JMEGASQ(MODE = 1)
001322
            BU CONTINUE
         C----CALCULATE AND PRINT INTERMEDIATE DATA FOR PSI MATRIX.
001327
               IF (IPRINT .EC. O ) GC TO 83
901330
               PRIST 294
001333
               DO 62 J=1, MODE
               PRINT 299. J. (PROB(I.J). I=1. HAINUSN )
001335
001353
            82 CCATINGE
001356
            83 DO 84 J#1,MODE
C01360
               PHI(1) . 0.
                                PHINUSN
031361
               00 84 l* L.
001363
               PHI(J) = PHI(J) + PRUD(1, J)+#2
            64 CONTINUE
031371
001376
               IF LIPRINT .EC. 0 ) GU TO 94
001317
               PRINT 29c. (PHI(I).INI. MODE )
         C
```

<sub>er</sub> tr∗ •

```
Ç
               MULTIFLY PROD BY THE ERROR VECTOR IN THE CONTROLLED MODES.
031411
            94 00 55 I= 1.MMINLSH
031413
               PRC02(1) = 0.0
001414
               DC 55 K# 1,MODE
001416
               PRCD2(1) = PRUD2(1) + PROUEL, KI + CN(K)
001425
            95 CCATIAUL
001432
               IF CIPRINT .EQ. O 1 GO TO 38
001433
               PRIM: 230. (PROD2(1), I=1, MM INUSM)
         C
               CALCULATE THE ERROR OF CONTROL.
031445
            98 CC 99 I=1. MMINUSN
3014¢7
               CRSSIII = QRIII - PRODZIII
001452
            99 CONTINUE
         Ç
               CALCULATE THE ORIGINAL ERROR IN THE CONTROLLED HODES, THE UNCON-
               TROLLED NUDES, THE ERROR GENERATED BY THE CONTRUL SYSTEM, AND
               THE ERROR OF CONTROL.
001454
               ECM . C.
001455
               3COM. I=1 001 00
001454
               S0411145 4 MJ3 * MJ3
GU1461
           100 CONTINUE
631463
               SCRIECH . SQRIECHE
001465
               £U# # 0.
001466
               DO 105 I+1, MMINUSM
901447
               SUM . EUM . + QREE; **2
001472
           105 CCATIAVE
021474
               SQRTELM = SQRT1EUM)
031476
               GD . ECM . EUM
001500
               SORTOD . SORTICO)
0J1502
               CRC - 0.0
001503
               DC 110 1=1, KMINUSM
001504
               CRC + CRC + PROD2:11+42
U01507
           110 CONTINUE
001511
               SURTERC . SCHILCRED
QJ1513
               CAS . 0.0
4J1514
               DO 115 I . LAMENUSH
001515
               CRS + CRS + CRSS(11 +42
061320
           115 CONTINUE
931522
               SCRICES . SCRICESI
```

```
EXPANL THE EFRUR OF CURTRUL VECTOR TO SE ELEMENTS WATH LEROS
              COPPESSONAING TO THE CONTROLLED MUDES. THEN MULTIPLY BY THE U MATRIX.
               TO CALCULATE THE FIRAL DEFLECTION VECTOR.
               DO 120 INI MAINUSE
031524
               HULDELLI . CKSSIII
031525
           120 CONTINUE
001532
00:532
               11 - 1
               N = 1
001533
               DC 133 1#1.58
001534
               IF (MCCC111) .EQ. 1) 123, 128
002536
031542
           123 CRSS(11) * 0.0
               11 * 11 * 1
031544
001545
               GO TC 133
           128 CRSSIII * HOLDINALE
031546
               N . R 4 1
001551
           133 CONTINUE
001552
031554
               00 136 1+1.58
               PRU-2(1) = 0.0
001554
               00 136 Jal.56
031557
               PROCEED * PROCEED + UCLID * CRSSED
10:100
631510
           136 CUNTINUE
               IF RIPHINT .EC. O 1 GC TG 137
01,574
               PRINT 255, (PRODELL), [#1:58)
601575
               CONVERT FUNCE VALUES TO POUNDE FOR PRINT DUT.
         C
           137 ATAM * ATAM * 1-25E-09
001536
031410
               ALPHSUM & ALPHSUM # 1.25E-09
               CG 138 INL. NACT
631611
               ALPSTORELS = ALPSTORELS = 1.25E-09
UJ1613
               ALPHAILS * ALPHAILS * 1.251-09
001415
           138 CUNTINGE
2119110
               PRINT 201, MODE, INJECTIE, ERL, MODEL
031021
               PRINT 200, (LUCATILL, 1-2, NACE &
031636
               PRINT 232. DNEWMAL
001651
               PHINT 246, EREPSTURELL, INLAMACT 1
301627
               IF INACT .LE. 8 1 PRINT 270
001672
               PRINT 254. ATAM
197160
               PRINT 25%, CALPHACIT, THIS MACT &
001707
               IF INACY .L. . B F PRINT 210
03:722
               PRIMI 253, ALPHSUM
ILLIED
UU1 731
               PAINT 251, ETE
```

```
031745
              PRINT 27% CO.SURTOU. ECH. SURTECH. EUM. SURTEUM. CKC. SURTCRG.
             1 Chis SURTORS
C31775
           350 CHATINUE
PC50F0
              SICE
201203
           202 FORPAT
                       1/ 18815.5 D E
302002
           203 FORMAT
                       1 6113.5 1
032002
           20% FURPAT (1-1. * THE EIGENVALUES CURRESPONDING TO THE EIGENVECTOR
             1847612 U.P/// . [7615.5/3]
G32002
           205 FURNAT (1H . // (8615.4) 1
632002
          206 FURNAT 120141
           201 CHRAT LIMI. MUMBER OF CONTROLLED MUDES # 4. 13./// # THEY ARE
002002
             J MCDES
                        *, 1215, (/19x, 1275 ) }
002002
           ZUB FLAMAT - EAH - 7- ACTUATOR LOCATIONS P. 1215; 1/19X; 1215} - F
C02662
           209 FURNAT (BAIC)
032002
          210 FORMAT (IH .// * MN PARTITION OF THE EIGENVECTUR MATRIX */)
632602
           211 FCRMAT (1H . //L BELD.4) 1
           213 FORMAT - (1H c//# THE GN PARTITION OF THE Q VECTOR IS *,
                                                                            11
022002
             1 (8815-4) )
           218 FORMAT (IN . // . MA INVERSE LISTED BY HUNS.4/ 1
032032
002002
           219 FORMAT - 11H -//* MATRIX TO CHECK MM INVERSION - SHOULD BE IDENTITY
             1 MATRIX. LISTED BY RUNS. # / 1
032002
           225 FURMAT - ELH 177 37X1 - MEAN SOUARE
                                                      KMS ERRURAS 37X,
             1 PERFORM, /// OX, TURIGINAL DISTURBANCEM: 4K; ZEES.4. // OX,
             2 OURIGINAL ENAUR INT. TA. 2610.6. John THE CONTRILLED MODEST //
             3 bx. #ORIGINAL EPROR IN THE#. 3x. 2816.4. / 64. *UNCONTROLLE
             4D MUDES# /// Ax. *ERRUR GENERATED IN THE *. 2810.4. / 6%.
             5 *UNCENTAULLED MODES att. / 6x, *CONTRUL SYSTEM*, // 6x. *ERROR D
             of CChirule, ex. 2816.4 1
935035
          230 FURPAI - ELK , FF - 66K PSI HATRIX + ERROR VECTOR LEARCH VECTOR IS
             I IN THE MODAL DONAINLE ./ # THIS COLUMN YE CTUR GIVES THE ERR
             ZUR CENEPATED IN EACH MCGE. # ///INFES.41 )
           231 FURNAT (1H1, /// * THE DETERMINANT APPEARS EXCESSIVELY LARGE OR
002062
             ISMALL. THE PUN WAS STUPPED. . 1
           232 FURNAT (IM .//E12.4. * IS THE VALUE OF THE NURMALIZED DETERMIN
632002
             TANT OF MY. IF THIS VALUE IS SMALL # / 15%. # COMPARED TO 1. THE
              2MATRIX IS ILL-CCHDITIONED.# 1
032002
           246 FURRAT (IN . / * FURCE SECTOR UNDER THE MODAL CONTROL LAW IPOUN
             1051.4// (E12.4. 7615.41 )
995095
           247 FURNAT ELH 4// E12.4. ILH . . 10**E.12.10UH*1UJ) IS THE VALUE
             THE THE CETERMINANT OF THE MATRIX ( (LAMPHIT * LLA MH) I USED IN
              28 INDING ALPHA., / Elb.s. . IS THE MORMALIZED DETERMINANT. IF THE
              35 VALUE IS SMALL CUMPARED TO I. THE MATRIX IS ILL-CONDITIONED. #1
632002
           250 FORMAT 11H . // * THE FURCE VECTOR UNDER THE OPTIMAL CONTROL LAW
```

```
1 (PCUNDS).*. // (512.4. 7E15.4) )
          251 FORMAT (1H . // * THE FINAL ERROR UNDER THE OPTIMAL CONTROL LAW
032002
             1 IS *, £15.4 1
          253 FGRHAT (1H . / * THE RSS VALUE OF THE FORCE VECTUR UNDER THE OP
202002
             ITIMAL CENTROL LAW IS+. E15.4. * POUNDS.* 1
          254 FORMAT (1H . / * THE RSS VALUE OF THE FORCE VECTOR UNDER THE MO
002002
             IDAL CENTROL LAW IS+. E15.4. * POUNDS.* )
002002
          255 FORMAT (1H . // * This column vector gives the deflection of th
             1E MIRROR AT EACH GRID PEINT. *2 / * UNITS ARE THE SAME AS THE DRI
             2GINAL W VECTOR. ** // (8E15.4) )
002002
          257 FORMAT (111 .// 31H LAMODA * H LISTED BY ROWS. .)
          258 FORMAT 11H .// 60H THE INVERSE OF ( (LAM*H)) * (LAM*H) ). LISTE
002002
                             ,/ )
             IU BY ROAS.
002002
          260 FORMAT (1H1, 8A10 )
002002
          261 FGRMAT (F10-4)
002002
          262 FOR MAT (1H . /// * ERRUR VECTOR. EACH TERM MULTIPLIED BY *.
             1 F10.4, // ( 6E15.4) )
002002
          270 FORMAT (1h )
002002
          294 FURMAT (IH : //// 995 THF MAIRIX PRODUCT -- LAMBDA(R) * H(R) *
             IN(N) INVERSE * LAMBGA(N) INVERSE -- LISTED BY COLUMNS. / * THIS
             2 HATREX IS CALLED THE PSI MATRIX. * 1
002002
          256 FORMAT (1H . // BOH THE DIAGONAL ELEMENTS OF THE PSI TRANSPOSE
             1* PSI MATRIX. . / 2 THESE ARE THE PHI SQUARED TERMS.* //
             2 (6515.4) }
002002
           299 FORMAT (16 , // * COLUMN NO. *, 14, // (86.5.41 )
002002
              ENC
```

ÇT			CCRRESPONDING	TO	44.5	ETCENVECTOR	MATRIY	
	THE	EIGENVALUES	CCKKEZHOMDING	10	ILE	EIGENTECION	741010	•

a many and a m

3.509708-02	3.5C880E-02	3.058606-02	2.94660E-03	2.50740E-03	2.504508-03	2.49790E-03	
8.98400E-04	8.97990E-04	5.6698JE-C4	4.89340E-04	4.89050E-04	3.446908-04	3.443306-04	
2.36100E-04	1.79640E-04	1.795105-04	1.79100E-04	1.703708-04	1.30350E-34	1.05800E-04	
1.0552 0E-04	9.19350E-05	9.181906-05	7.49770E-05	7.08320E-05	7.0034UE-05	5.64260E-05	
5.291108-05	5.246308-05	5.100906-05	5.0974UE-05	4.503536-05	3.87970£-05	3.87810E~05	
· 3.58890E-05	3.35360E-05	3.347706-65	3.21660E-05	2.946801-05	4.79760E-05	2.753AGE-05	
2.74800E-05	2.47400E-65	2.230906-05	2.22750E-05	2-048435-05	2-047408-05	2.012906-05	
2.011706-05	1.956906-05	1.86400E-05	1.59650E-05	1.545206-05	1.577706-05	1.57630E05	
1.31130E-05	1.368208-05						
THE ERROR VECTOR	15 UINV + ERI	KOR EXAMPLE NO.	1				
-1.7184E+01	-1.2100E+01	7.54586+00	-1.1009E+01	-3.6741E+00	2.7612E+00	-1.5698E+01	-1.4058E+00
3.95298+00	-1.2562E+01	9.2392E-C1	-9.0744E-01	-2.1174E-01	1.04008+00	5.38536+00	1.6003E-01
6.1081E-01	-1.3558E+00	-2.044JE+CO	-1.1568E+90	9.7822E-02	-2.79516+00	-2.7975E-01	5.3307E-02
-1.2237E+00	-3.4520E-01	-5.0349E-01	-3.7334E+00	3.824ot-01	9-60296-01	6.2557E-Q2	5.9744E-01
2.557GE-01	-3, 4355E-C2	-7.6660E-G1	-2.55CTE+00	7.92098-01	6.0366E-01	-8.8766E-02	4.34186-02
3.7177E-01	5.6847E-01	-7.4978E-01	5.1375E-01	6.02086-01	4.1136E-02	-3.2221E-01	-1.3675E-01
-8.5519E-02	2.4347E-01	4.5058E-C1	6.1734E-02	1.0936E-01	2.11406-01	-1.9399E-01	2.49916-01
-2.05756-01	5.1006E-02				***************************************		
ERROR VECTOR: EA	CH TERM MULTIP	LiED BY 1.0	900				
-1.71840+01	-1.2100E+01	7.4458E+CO	-1.1009E+01	-3.07÷1E+00	2.7012E+00	-1.5498E+01	-1.4058E+00
3.95298+00	-1.2562E+01	9.2392E-C1	-9.0744E-01	-2.1174E-01	1-0400E+00	5.38535+00	1.6003E-01
6.1081E-01	-1.3558E+00	-2.04406+00	-1.1568E+00	9.1822E-02	-2.79818+00	-2.7975E-01	5.3307E-02
-1.2237E+90	-3.6520E-01	-5-0349E-C1	-3.7334E+Q0	3.82466-01	9.60298-01	6.2557E-02	5.9744E-01
2.5570E-01	-3.43556-02	-7.66006-01	-2.55C7E+00	7.92046-01	6.0366E-01	-8.8768E-02	4.3418E-02
3.7177E-01	5.6847E-01	-7.4978E-01	5.1395E-01	6.0208E-01	4.1106E-02	-3.22216-01	-1.3675E-01
-8.5519E-02	2.4347E-01	4.5098t-01	6.1734E-02	1.0936E-01	2.1140E-01	-1.93996-01	2.4991E-01
-2.0575E-01	5.1C06E-02		<del></del>			*****	

MUMBEK	U٢	CLNI	YOULED	MUDE 2	=	フ

THEY	ARE	HUDES	1	2	3	4	5
ACTUA	TGR	LOCATIONS	Ž	30	21	44	45

# HN PARTITION OF THE EIGENVECTOR MATRIX

3.03958-02	7.6825E-04	1.3983E-C3	9•9971E-03	-1.0324E-02
-1.6167E-02	-1.1727E-02	3.0486E-02	7.28798-03	5.19905-03
-3.3+79E-02	-2.2867E-02	-4.2840E-C2	-4.5298E-02	-2.2785E-02
-1.22906-02	-1.48018-02	-3.4064E-02	-5.48178-02	-1.4533E-02
1.72546-02	2.7355E-02	2.2451E-G2	1.8150E-C2	<b>-5.5135E-</b> 02
		UR IS	N CE THE Q VEGT	THE GN PARTITION
-3.0741E+00	-1.1009E+01	7.4458E+CO	-1.2100E+C1	-1.7184E+01
			TEC BY FCWS.	HN INVERSE LIST
-1.1731E+01	6.U853E+00	-1.5412E+01	-5.71416+00	-1.1002E+01
-2.9008E+00	-3.9150E+01	2.54646+01	-6.3121E+00	1.0608E+01
\$.53766+00	2.05536+01	-1.9352E+C1	2.4583E+G1	-3.1447E+0C
1.2737E+01	1-25826+01	-2.4137E+C1	-2.72375+01	-4.3643E+01
-3.87698+00	1.3938E+01	-1.2536E+Cl	-4.24138-01	2.6971E+01

1.00000 +00	-4.7740E-15	-5.3291E-15	>.3291E-15	-2.6645E-15
-3.5527E-15	1.0000E+00	4.4409E-15	-3.5527E-15	-8.8818E-16
3.55276-15	1.53776-14	1.C000E+00	-1.0658E-14	-2,6045E-15
0.	3.69158-15	2.13168-14	1.00005+00	-0.0613E 16
5.32916-15	-1.2018E-14	-4.88186-15	1.24346-14	1.00008+00
LAMBDA + H LI	STEE BY ROWS.			
5.92001E-12	E.4506ZE-11	2.82445E-11	5.634368-12	4.36641E-11

2.1982E-73 \* 10\*4 0\*1001 IS THE VALUE OF THE DETERMINANT OF THE MATRIX ( (LAM\*H)) \* (LAM\*H) ) USED IN FINDING ALPHA.
1.81460E-05 IS THE NORMALIZED DETERMINANT. IF THIS YALUE IS SMALL COMPARED TO 1. THE MATRIX IS ILL-COMDITIONED.

THE INVERSE OF I ILANHHIT + ILANHHI I. LISTED BY ROWS.

1.01745£+15	-1,816428+15	-4.22980E+14	-5.26994E+14	2.2245 SE +15
-1.337086+15	-1.227506+15	-2.102/2E+15	3, #75206+15	-5.26994E+14
4.47075E+14	1.29669E+15	1.413476+15	-2.16272E+15	-4.22980E+14
-4.8>07UE+14	2.581356+15	1.296646 +15	-1.22750E+15	-1.61642E+15
8.616368+14	~4.85070E+14	4.47075E+14	-1.337C8E+15	1.017950+15

THE HATRIX PRODUCT -- LAMBDAIR) + HIR) + HIR) + HIR) INVERSE + LAMBDAIR) INVERSE -- LISTED BY COLUMNS. THIS MATRIX IS CALLED THE PSI MATRIX.

COLUMN NO. 1

-6.99261-02	-1.8712E-02	-2.8060E-C2	3.3064E-02	-3.5960E-02	-1.1681E-02	2.6704E-07	-1.0880E-02
1.02+26-02	1.1800E-03	1.61 Ne+C3	92036-03	-6.79106-03	-1.3398E-02	-5.2258E-03	-1.2386E-03
-3.416 it-U3	-3.48032-04	-7.28126-03	-6.3705E-03	-9.4871E-03	2.7494E-03	-3.31956-03	1.25485-03
					-1.99055-34	1.22058-03	-1.389+E-03
3.5813E-03	4.1392F-03	3.3449E-C3	3.071404	-7.503BE-04	• • • • • • • • • • • • • • • • • • • •		
2.2993E-03	4.62U1E-03	1.35374.03	1.6704E-03	4. 3943E-03	1.0575E-04	-2.23758-03	3.65536-03
-9.72428-04	7.15936-05	2.68496-34	1.9872E-44	-2.2887E-03	-8.23136-04	-2.16475-03	9,16996-04
8.4294E-04	9.454UE- <b>0</b> 4	#.\$384E-C4	1.3525E-03	4.1d43L-U4			
				•			
COLUMN NG.	2						
-6.40955-02	-1.4076E-01	1.65096 -02	4.9403E-02	-2.88498-02	-1.7861E·u3	4.0145E-03	-1.2093E-02
-8-3515E-03	- 5.8100E-03	6.61668-03	-1,3067E-03	-6.4.276-0.	-9.8692E-03	-6.5430E-03	2.94238-03
*****	3.7481E-03	-5.3932E-03	-4.7038E-03	-1.3.538-03	-1.8702E-03	-4-6569E-03	-1.0951E-03
-2.20168-04				-1.32142-03	*	-2.5247E-04	7.49436-64
-1.452cE-03	1.5910E-03	2.7064E-C3	-1.0571E-03		1.0486E-04		
4.15536-04	2.2332E-03	-1.82,74-03	-2.31ChF-05	-3.1824E-04	-4.23598-04	-1.4516E-03	1.3178E-03
-4.4038E-04	-4.5967E-U+	1.6059E-01	-3.040+6-05	-0.8036E-04	-7.0412E-04	-1.17456-03	2.0333E-03
1.72326-04	-1.55876-04	3.90066-04	-4.4464E-04	-1.3610t-05			
COLUMN NO.	3						
9.53416-03	-1.6932E-01	-1.1545E-02	1.9781E-02	-6.9.026-02	-1.6185E-J2	-1.6243E-02	-2.9674E-02
3.82986-03	1.26666-02	5.71356~44	8.0743E-C4	-4.3301E-03	-1.00436+02	9.13686-23	~6.ú4v2E-03
-1.64426-03	8-17005-04	-2.3389t-C3	-4.0446E-03	~1.6870E~03	4.42136-04	-1.2591E-03	-1.70086-03
4.22491-03	-1.97415-03	3.45748-83	8.46375-44	1.29775-03	1.06296-03	-0.8240E-04	-3.9145E-04
1.54146-03	4.5929E-03	1.07+26-03	-9.6061E-04	3.71225-03	7.24815-74	~5.8U27E-04	2.5045E-03
9-31936-04	1.043F-03	-2.49276-03	4.5725E-04	6.24936-04	-4.2155E-04	1.0091E-04	-9.3585E-04
-9.72416-05	2.17388-04	-8.5882E-C4	1.7504E-03	2.70008-04			
COLUMN NU.	4						
-1.6776E-01	1.7128E+CO	1.7735€-01	-2.7455E-01	0.0177E-01	7.33498-02	2-25538-01	2.9817E-01
-4.02496-02	-1.9457E-01	-5.1cC3E-C2	-3.0342E-02	-4.4345E-UZ	9.66638-02	-1.02885-01	8.0014E-02
4.26956-62	-3.1075E-02	-2.29936-02	1.9326E-02	1.52596-02	-4.3653E-03	-1.1782E-02	2.7942E-02
-6.1520E-02	1.1913E-02	-1.4954E-C2	-9.2634E-03	-1.23416-02	-6.7831E-03	1-49856-02	4.94556-03
-1.74.75-02	-3.5102E-02	-1.15G4c-02	1.10+2E-02	07 37E-32	-9.3192E-u3	-1.9354E-03	-2.4149E-UZ
		3.00446-0"	-7.9081E-03	-1.3497E-02	9938E-03	-1.4550E-02	1.4446-02
-1.13781-02	-1.78248-02				~4.97305~03	-1443306-02	1164405-02
-1.3354E-03	-5.05606-03	1.51536-02	-1.94"15"02	-6.89476-03			
COLUMN NO.	5						
1.1112E-01	1.90478-01	-9.7258E-Q2	-4.0842E-G2	1.3189E-02	8.8094E-02	1.29826-01	6.9740E-02
-1.9080E-G1	-2.01016-C2	-7.6412E-02	1.7205E-02	4.5282E-02	-4.2258t-04	-8.3280t-03	1.6290E-02
4.25248-03	-4.6043E-02	3-1884c-C2	-6.300ZE-04	44 33E-02	4.4079E-03	-5.9319E-03	-1.1486E-02
~1.4011E-02	-3.74946-02	-1.8610£-02	-3.6419E-33	3.74666-05	-2.5785E-03	-2.96748-03	-3.20215-03
-8.1581E-03	-3.18086-03	-8.G0766+03	-3.2387E-03	-1.3229E-02	1.1136E-02	5.69248-04	-1.3500E-02
1.79415-02	-3.6309E-04	<b>6.30456-03</b>	-7.1931E-03	0.501+1-03	-5.5240E-04	6.68696-04	-2.08935-04
	• • • • • • •				- 3.32745-47	11 4 0 0 11 TL - UT	6.00735-04
-8.6667E-U3	-5.50436+63	~2.2285£~ <b>C</b> 3	-4.0112E-03	-1.02511-03			

9.32945-03

MET MATRIX A CORDE USCYOR ALCORD VECTOR IS IN THE MODEL OFMAIN.

2.4120E-02 3.6231E-02 3.6638E+00

PST MATRIX *	ERROR VS	CIOR (ERRI	DK AFCLT	:N 12 IN 15	HE MUURE	D.MYTM* 5
THIS COLUM	IN VECTOR	GIVES TH	M.RRS 3	CEMERITED	IN EACH	MODE.

3.4865E+00	-1.8792E+#1	-1.40368+00	2.15406+00	-6.125(E+00	-1.02436-30	-3.17536+00	-3.4244E+00
1.09735+00	2.36016+00	7.29525-01	3.77196-01	4.75428-01	-#.3688E-01	1.40026+00	-1.012:F+00
-4.364 0E-01	4.77981-01	3.0895E-01	-7.4174E-02	-1.4057E-01	8.381/E-03	2.55514-01	-2.8656E-01
7.1504E-01	-9.7937E-02	1.6853E-CL	1.29146-01	1.65176-01	9.42158 -02	-1.7655E-01	-3.0788E-02
1.66996-01	3.2590E-01	1-6284E-01	-1.4525E-01	4.80136-01	7-03876-02	7.0909E-02	2.55358-01
8.8498E-02	2. C\$36E-01	-4.0.78E-01	1.1460E-01	1.76996-01	7.65676-02	2.0817E-01	-2.2762E-01
2-82506-02	4 /81 7F=03	-1-6442F-01	2-26776-01	7. 14.1 75-02			

THIS COLUMN VECTOR GIVES THE DEFLECTION OF THE MIRROR AT EACH GRID PUINT. UNITS ARE THE SAME AS THE ORIGINAL  $\boldsymbol{w}$  vector.

-2.23378-01	-4.63:58-01	-2.2454E-C:	-2.6740F-02	-7.3074E-01	-2.4536E-01	-6-1407E-01	-1.08656-01
4-1102F-01	-5.8820F01	7.7151E-C2	7.77098-01	4.5373E-01	-2.6323E-01	1-16986-01	8.0724E-01
-4.2389E-02	-1.39226-0:	2.37032-01	2.7446-02	1.051eE+00	4.2J02E-01	-1.10428-01	4.5738E-01
3.91176-01	-4.0947E-01	6.3+16E-G2	2.3595E-01	1.7538E-01	B.1325E-02	6.3272E-01	-1.4576E-01
8.77935-02	-2.73995-02	4.7060E-31	-5.4019E-01	3.43758-01	-1.8325E-01	1.35762-01	-3.5522E-01
-5.75751-01	-4.5873E-01	-2.3912E-C1	-4.90206-01	2.45+65-01	1.97396-01	-3.43126-01	-0.7047E-G1
-1.14466+00	-\$.4857E-61	-2.57126-01	-6.09C9E-02	3.59536-01	3-29-8E-01	5.4920E-01	-3.4262E-02
m1 - 415.65 - 01	1.4C05F-01						

APPENDIX A - Continued

THEY ARE MODES 1 2 3 4 5

ACTUATOR LOCATIONS 2 30 31 44 45

1.5384E-01 IS THE VALUE OF THE NURMALIZED DETERMINANT OF HN. IF THIS VALUE IS SHALL COMPARED TO 1. THE MATRIX IS ILL-CONDITIONED.

FURCE VECTOR UNDER THE AUGAL CENTROL LAW IPOUNDS !-

-2.4256E-02 1.5213E+00 -1.2070E+00 -5.0983E-01 -1.8129E-01

THE RSS VALUE OF THE FORCE VECTOR UNDER THE MODAL CONTROL LAW IS 2.4534E+00 PJUNDS.

THE FORCE VECTOR UNDER THE OPTIMAL CONTRUL LAW (POUNDS).

-6.5569E-02 1.6345F+00 -1.1433E+00 -4.3576E-01 -7.0d3JE-01

THE RSS VALUE OF THE FORCE VECTOR UNDER THE UPTIMAL CENTROL LAW IS 2.3360E+00 POUNDS.

THE FINAL ERROR UNCER THE OPTIMAL CONTROL LAW IS 1-1336E+01

	MEAN SQUARE ERROR	RMS ERROR
ORIGINAL DISTURBANCE	1.13608+03	3.37136+01
CRIGINAL ERROR IN THE CONTROLLED MOCES	6.21846+02	2.5136E+01
ORIGINAL ERROR IN THE UNCONTROLLED MGCES	5.04736+02	2.246671
ERROR GENERATED IN THE UNCONTROLLED MODES BY CONTROL SYSTEM	<b>4.</b> 4596€+02	2.11186+01
ERROR OF CONTECL	1+36716+02	1.1423E+01

## APPENDIX B

## EIGENVECTORS OF THE MIRROR

This appendix contains a listing of the U matrix (matrix of eigenvectors) for the 76-cm-diameter (30-inch) thin mirror. This matrix was obtained from the SAMIS program in reference 4. A more graphic display of the first 10 eigenvectors is contained in appendix C. The eigenvalues associated with each eigenvector are given in appendix D. Lambda(1) is associated with column (1), and so forth. The diagonal mass matrix m is also given in appendix D. The U matrix is orthogonal with respect to the mass matrix (refs. 4 and 5):

 $U^{T}mU = I$ 

	-3.441-02 1.14E-04 5.43E-02 -8.21F-02 -3.71F-02 1.31F-04 3.74F-02 8.24E-02 -6.14E-02 -3.45E-02 -1.21F-02 7.55E-05 1.27F-02 3.47F-02
A WELLE FITTED BA CEFAINE	# 45-02 - 4.2 k-03 1.456-04 4.418-41 5.256-45 -9.128-47 -5.118-45
Milole Milole Milor Milor	
widelle widerly villouts	7.555-02 1.515-02 -7.675-02 -7.177-05 1.755-03 -1.936-07 -4.576-02
•	1.44-02 -1.316-02 -1.44-1- 20-14-1- 20-14-02 -1.44-02 -1.
•	4.17F-02 3.44-02
COLUMN NU. E OF U PAIRLE	
* *	COLUMN NO. F OF U MATRIX
- m2.45f-82 - e1.89f-02   ju45z-03 - n4.4f1-02 - n2.44f-02 - f1.52f-02 - n4.4f1-03 えっと作っきる - f1.3 jf n8.7 - n4.6 5-02 - n7.755-72 - f1.17f-02 - n4.66-73 - 3.47f-03	-1./0t-32 -7.216-03 1.69c-02 -2.46f-02 -7.516-03 -8.386-05 7.56f-03 2.49f-02 -2.416-02 -5.726-03 -4.576-03 -4.516-05 -5.656-03 5.10f-03
-7.15-03 -7.15-02 -6. 46-02 -1. CAE-072 -11.795-02 -3.546-06 -1.486-73	2.40C-02 -2.12E-02 3.461-04 1.47E-02 1.07E-02 -2.09E-04 -1.42E-02
1.628-62 1.90-92 1.00.03 -0.375-0	-1.076-02 -3.946-04 2.131-02 1.147-04 2.748-02 1.648-09 3.658-09 c.426-09 -3.048-02 -3.646-02 4.748-02 -1.678-04 1.148-02 4.748-02
	3.05E-02 5.30E-02 Ti.14F-07 /.44F-05 -0.25E-02 -5.29E-02 -3.44E-02
##.106-92	#-52E-03 4-57E-02 7.19E-02 5-57E-07 2.01E-06 -5.55E-07 -7.19E-07 -4-58E-02 -8-39E-03 6-87E-02 9-68E-07 6-77E-07 -2-79E-05 -6-78E-07
5.556-02 1.7 16-02	-9.69E-02 -6.87E-0/
COLUMN NJ. 2 OF U MATAIK	
	COLJAN NO. 8 OF U MATRIX
	-9.895-03 3.095-02 -9.72+-03 -4.445-07 2.485-02 5.835-02 2.612-82 -4.635-02 -7.445-02 -7.46-04 4.721-37 5.065-07 4.735-02 -7.885-04
9.2%-02 -0.5%-72 -4.4%-02 -2.66-07 -1.15%-02 1.76%-04 2.07%-02	
4.746-02 7.896-02 1.126-01 -4.767-07 -3.246-02 -2.076-02 -1.236-82	2.54E-02 -1.08E-02 -4.52E-02 1.33F-82 2.54F-82 9.38E-03 -2.53E-02
es ese : 10-45 - 10-310-9- to 110.5 - 12-31 - 50-130-1 - 12-30-1-	90-170,00 90-170,0 90-100,0 90-400,0 00-100,0 90-310,00 90-315,00 90-470,00
*1.40f-02 *1.417-02 -1.621-02 *2.400 02 *3.48f-02 *2.41f-02 *1.41f-02 *4.41f-02 *4.41f	3.556-02 -3.567-02 -4.214-12 -2.506-02 2.148-02 -2.506-02 -4.218-02
4.818-03 3.346-87 -4.731-03 -2.107-82 -3.448-82 -4.628-82 -4.441-82 -3.568-92 -2.028-92	**************************************
	-30045.494 -38444.404
CULUM NO. 3 OF W MATRIX	CULUMN NU. S of MAINIX
-1.6%-62 -2.2%-02 -1.636-02 -3.146-07 -3.516-07 -5.776-02 -3.516-02	-3.556-02 -4.6.6-05 3.556-02 -3.026-02 -3.386-02 -8.486-05 3.376-02
-3.14E-02 -4.17E-02 -4.14E-02 -4.20F-02 -4.16F-02 -4.20F-02 -4.14F-02 -4.17E-02 -4.58E-02 -4.57E-02 -4.49E-02 -4.61E-02 -4.21F-02 -4.61E-02	3.04E-02 2.0E-07 -2.99E-02 -3.87E-07 -7.43E-05 3.81E-07 2.44E-07
	-1./le-0./ l.inc-01 l.aft-02 -n.n/t-0/ -4.50f-02 l.52f-06 4.5ft-02 n.n/t-02 -1.8nf-02 -l.b.n-01 l.anf-02 -1.40f-07 -5.44f-02 -n.sft-02
	#.#(E-DZ =1.##F-OZ =2.En.=01 7.##F-OZ =1.#0F-OZ =5.9#F-OZ =4.17F-OZ #.12E-O5 #.19F-OZ 5.9#F-OZ 1.3#F-OZ =7.#9E-OZ 2.50F-OZ =2.[7F-OZ
-3,301-02 -3,791-02 -3,121-02 -4,591-07 -4,371-07 -3,751-02 -3,501-07 -1,631-02 -3,351-02 -3,351-02 -3,351-02	-3. 45-32 -5.0% -02 -2.5%-02 1.7% -05 2.8%-02 5.0%-02 3.44*-02
-2.29E-32 -1.0EE-02 -1.00E-02 -1.2E-03 -4.30E-02 -4.33E-02 -4.28E-02	-4.532-03 -2.582-42 -5.112-03 1.551-07 -3.181-05 -1.531-07 5.892-03 2.677-02 9.225-41 2.642-92 5.581-07 5.041-02 -1.741-04 -5.041-07
-3.24E-02 -1.66E-02	-5-51t-U2 -2-41t-02
CALLING NO. 4 OF U MAIRIE	
	COLUMN 4.1. 10 OF J MAINTA
\$-+86-03 -156-	5.44E-02 5.41E-02 5.14E-02 4.4E-02 4.49F-42 2.49F-02 4.81F-02
#4.5E-02 9.94E-02 3.86E-02 -1.59E-02 -9.20E-02 -4.40E-02 -9.20E-02	0.001-02 -2.776-07 0.071-03 -0.071-03 -9.076-07 -9.076-03 6.001-03 -7.376-02 -7.376-02 -2.006-02 -1.006-07 -0.006-02 -0.006-02 -0.006-02
-1.551-02 3.861-02 9.961-02 0.961-02 8.951-03 -3.411-02 -3.481-02 -5.211-02 -5.901-02 -3.411-02 8.951-03 0.461-02 2.551-02 -3.411-02	-1.43E-02 -2.80E-02 -7.35E-02 -2.14-07 4.13E-03 -5.07E-03 -3.02E-02
-9,316-82 -9,686-82 -9,616-02 8,556-83 0,666-82 2,656-82 -1,616-92 -1,366-82 -3,686-82 2,896-82 -1,566-82 -3,646-82 -7,646-82 -1,246-82	-4.761-02 -3.871-02 -5.071-03 0.141-03 -2.141-07 4.111-07 44.781-08 4.871-02 2.401-02 4.142-02 -1.641-07 44.781-01 2.401 62 4.871-02
5.279-02 ~1.486-02 +1.236-02 4.02f-04 3.02f-03 5.03f-03 -1.236-02	5.316-92 3.706-92 0.346-92 0.617-03 -2.666-72 6.81F-03 4.788-02
-1.981-02 5.1%-03 5.301-03 2.861-02 6.641-02 9.441-02 6.661-02 2.411-02 5.311-03	5.70E-02 5.33E-02 5.13E-02 J.19F-02 -7.18E-02 -7.26F-02 -2.10E-02
••••	3.950-02 5.130-02
CDLUMM NG. S OF U NATER	Cucama nu. 11 ut u matria
-6.45E-02 -9.67E-02 -9.67E-02 -9.101-03 -9.86E-02 -9.73E-02 -4.C6E-02	-mwt-g2 -1.15f-g2 -7.99, 02 -1.52f-g2 -1.57f-06 \$.50f-g2 2.43f-g2
	1.14f 02 -5.00-02 -5.47t-02 -5.44f-02 -4.48f-02 -4.18f-04 4.38f-02
2.176-92 1.874-92 2.756 92 3.496-92 5 51-32 1.266-97 7.676-87	#.410-07 5.4:1-02 4.94-02 -4.70-03 -2.136-02 -3.345-02 -2.036-02 1.336-04 2.036-02 3.346-02 2.106-07 4.556-03 7.146-02 1.406-03
4.165-02 3.17c-02 7.23b-02 1.555-02 7.485-02 3.176-02 6.751-62 5.666-02 2.766-02 7.786-02 2.026-07 5.656-04 1.0 5-02 1.786-02	3.1#1-02 4.832-03 -7.1702 5.09-64 -4.365-63 -4.665-63 -3.187-02
2.746-87 5.1M-62 -5.246-83 -7.978-83 -1.477-82 -2.578-82 -1.496-82	#./DI-02
-7.01E-83 -4.0(E-01	-0.01F-03 1.05c-01

CULUMN NO. . . OF J MATRIX

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COLUMN NO.	te or uni	****					CALVAN MIL	LA UFUN	41912				
~4. 52i -82	-3.196-42	*4.* 12 * 02	-4,375-82	-7.516-07	-4.5¥~03	-2.534-02	~. 634 - 63	3,431-85	4,C21-9/	-6-11-03	1.101-07	-1.445-05	-1.017-0
- 4. 446 - 07	+ . 7 H - C3	7.516-01	1.5-47	7.771-07	1.015-62	1.476-01	4.1 b - 43	1.041-32	3.44-24	1.874-07	-1.0 M-0.	-1.8W-37	-4.00F-0
-1.571-01	2.14 - 22	J. 194 - 82	J. Laf - 07	7.447-67	-1.115-05	7.500-02	-1.306.87	- 3. 4 IE- DC	2.14-47	1.517-87	-2.938-02	2-146-07	2.9/1-8
1 > 6-02	3.2 M - 62	2.4.1-42	1 - 0 of - 67	40 - 44 I . S	7.041 -07	-1.2*1-02	+1.715-02	*2.1 Pt -02	3.901-02	-3.411-03	8.475-93	-3.111-07	-4.275-0
7.17. 01	-1-141-42	2.124-62	J. 1 # - 62	1.948-62	+4,316-02	· 1. *&F-#?	4.11/-65	0.14-07	3.371-07	-4.5 W-01	7.476-07	4.526-03	-5.825-8
·2.136-01	3.84-63	-3-411-02	-1.445-07	-1.925-07	3.601-61	-2.114-01	1-411-02	-2.104-02	-4. 304-03	-2.476-01	5.975-02	2.104-02	-1.811-8
BBE-02	1.811-92	6.10.02	-1-101-07	-0.545-07	-2.516 02	1.971-07	144.42	5.836-8"	2.474-02	-4.3/F-82	-3.5EF-05	4.565-87	-2.415 -0
1. 778-02	- >. 0 0c - D2	9. 542-02	7. 947 - 87	-9.60-03	-5.901-02	-4.704-41	+5.441-92	-7.011-07	1.171-91	1, さゲーリナ	-8.626-42	0.5 N ~ 05	8.821-0
7. 716 -02	1.481-02		• • • • • • • • • • • • • • • • • • • •				10-10-4	-1.171-01					
	******												
CHEUMH 43.	(3 to y P)	.Tejz					COLUMB MIS	[9 (3 y m.	ATEIR	•			
-2.3>6-82	7.830-11		7.575-04	-3,411-07	9.447-04	3.947-07	-1./12.02	0.17-07	-1.251-02	-5.290-07	2.015-02	4.146-02	2.838-8
-1. ++6-81	4.3 M . 22	. 3.041-02		4,27,+84	9.478-43	3.5-1-07		8.54-81	-3.676-82	6. 14 - 77	3.491-43	4.717-03	-2.678-8
4.416-02	1.0 - 31	- 5. + ct - 03	~5. 171-67	-2.14-02	4. * 27 - 66	2.278-02	4.474.83	10.3 24 - 01	-1. **L -#3	-3.516-67	-7.398-87	-2.415-82	-2 47-4
3.051-07	3.54 - 93	-1.35. ·01	- 4. 701 - 63	-1.191-87	2 46 - D4	3.098-67	-3.311-02	-7.98-03	1-454-01	7. 0 37 - 41	-2.177-62	3.446-63	1.198-0
2-174-00	+3-111-92	-1 745-01	3.2-7-42	L. 64-03	-4.2W-02	5.:96-42	-1-14-82	1.1# -03	3.01.01	-2.7 F 67	7.417-45	-9.236-02	5.914-0
1.2H-06	50- # 6.4	9.300 02	8. 5 FF - 4%	-5.08F-8/	-6.44 -02	-1.161-67	1.801.42	4.454 -03	-5-231 -42	-3.444-87	4,43F-01	6.45F-82	2.161-8
4.376.02	4. ** - 82	5.41t-72	4. 4M - 81	8.04F-05	+3,431-03	-5.194-07	-1.9:4-85	10-11 4.0	2.921-82	-2.47f-02	-2.9.1-03	-7.658-07	2.926-8
->-2 12 -22	1.334-42	1-271-03	- 4. 3 15 - 62	-6.99 -02	-1.421-43	0.918-67	0-311-02	-1.011-22	-1.151-02	- > 2 34 - 97	7.146-63	1.24-01	7.176-0
4.421-92	19-116.4-						-5-251-42	-1.154-07					
Lakuaha bir.	14 01 0 4	**					Carridge St.	20 ∪+ J≖	49471				
									. ,				5.74F-0
-3.475-83	5.60 02	-3. +01-03	-3.611-02	7.765-02	7.445-87	3.44-07	1.44.07	-3-04-96	-J. 0-t -0!	2. 1 /6 - 97 - n. a w - 07	-5.74F-07 1.67F-06	1.335-84 4.844-07	3.746+0
2.401-01	-4.+01 42	-1-421-01	3.031-03	1.456-02	1,456-87	-1.717-02	-2-1267	3.0 at -0.	-5.721-02		-7.1 W -44	2.016-07	2.1:6-6
4.474-08	3.8 H #2	-3.[/(-01	-2.9 11 -62	-1-211-07	2.274-04	-1.547-67	- 1-496 -07	2.054-04	1.44.94	1.514-04	7,114.44	4. 697-02	-3.4 M-W
	- 8. 111 - 41	6.0% 47	1.44-07	-2.101-02	-4.454-62	-1.077-82	-4.3 [1-05	-1.014-00	-2.071-04	- 1. 187 - 02	1,106-07	-2.134-02	-4.455-0
3.406-01	-1.111-32	-5.616-44	· ( . 190 - 87	7-631-07	2.461-07	2.771-07	1-141-36	5.411 -44	1-82	-5. 151-87			-5.186-8
*** # 1 B . C .	+ 3.4 St - 6/	2.544 82	5. 59F-87	2.844-07	1. 745- 77	-5.241-02	2.146-27	-0.441-83	C.134-01	3.492-57	6.456-02	6.15F-05 5.79F-02	5.110-0
1.34(-0:	-1.44 -32	1. 116-02	4.694-07	4-616-61	4.011-0.	1.515-42	-3.436-47	3.564-0-	+9. IH-02	-3, 792-67	-5.19F-04		3.110-4
-2.876-82	1.394 6.	1 - 428 - 42	2. 425 -01	-3.246.01	-i.7#F-31	-3.401-02	-5.611-04	1.0 % -07	3.1.6-47	4. LM - 01	1.821-82	5.39F-04	-3.02E-0
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1.015-07	3,214-113	3.411-02	3. caf- 0)	-9. /01-61	-3.645-8*	-9.701-61	**111-07	-2.404-93	4.111-92	2.2 M - 62	-7.86F-82	-1,441-07	-7.941-0
5.044-07	8.0 m - 82	-4.412-07	-1-611-87	1.075-07	-1.246-37	-4.4.1-07	2.441-42	-1.0 R -02	-4. fet-#2	-4.701-93	6.116-27	-4.76F-01	-4.846-0
1.4+1-67	4.27-07	-5.011-86	**. + 16 - 67	1.141-52	1.817-61	1.761-07	11.371 22	e.1# -07	- 3. byt - 42	-1. +04 - 93	5.214-92	1.435-04	5.206-8
50-10+.	-3.441-07	4.111-02	1. HH-6.	- 6. 844 - 07	-1.841-02	4.0-1-47	*3-nat -2)	-1.44 - 92	6-101-02	1. (11 -07	1.145-47	4.44-42	-3.041-0
2.74 -04	>.346-03	-1. +-4-64	*~. #4 #7		1.415-63	-1.976 47	-1.14E-31	-1-241-02	4. 6 M - 82	1.14-02	1.711-07	-2.124-02	-0.241-8
-v. +28-81	-3.4 H - 81	1.012-07	- 6 - 6 16 - 07	-1.845-07	-4.4 27.41	. 4.4 25-03	2. 421-82	7.1 M -01	-2-1/1-02	7.14-01	-4.741-02	7.107-05	7.481-0
4.33E D.	2.84 -08	-+	101 -07	-5.521-02	-4.481-07	-9.104-61	-2-351-02	1.044-33	4.211-03	1. 104 - 67	7.406-67	4.104-02	4,711-0
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4.111-03 1.111-02	1.121-07	4-471-36	3. 544 -87	5.871 -67	-1.710-07	4.445-63	من - فرو رو	- 7. 3 W - G2	111-02	1,241-97		1.404-62	-7.976-6
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#.912 -03 3.1 M -02 7.2 M -03 7.2 M -03 7.2 M -92 3.4 M -93	1.53(-07 52-111.8 50-4-11 6-9-11-11	4.071-02 -3.312-02 -112-02 -1131-02	9. Car +87 -1.015- U7 -7.8 17-87	\$,875-67 8,744-65 +74575-07	1.447-07	+7.16f-51 -1.64f-07	"30 4 41 - 82 30 4 41 - 82 12 4 4 4 43 13 4 4 4 4	-1.10-07 -4.00 -31 -5.5et-07 -5.04-07	2 - 64 - 64 - 3 - 64 - 64 - 1 - 41 - 41	-1.17 - 67	7.92F 67	1.105-82	1.997-6
#. # # # # # # # # # # # # # # # # # #	1.171-07 1.11-07 1.11-07 1.44-07 1.44-07 1.171-07	ALUTE-DE TACTES ME TACTES ME TACTES ME	5-Can-487 -2-015-UF -7-6-57 -7-67-87 1-447-83	5,878-67 8,746-65 -745-67 6,011-03	1.447-02 -7.45 -07 4.475-07	*7.165-93 *5:645-07 7:449-03	TBUTTE TO T	-1.1007 -0.501-07 -0.501-07 -0.501-07	*1414 *********************************	- 3.17 - C7 - 4.4 - C7 - 2.4 - C7 - 2.4 - C7	7,92F 67 -7,86F-96 -1,47F-97	1.40f-47 4.40f-47 2.71f-66	1,495-6
#1.912 -03 #1.924 -02 ************************************	1.52/-07 1.71/-62 1.4-02 	Surfel S	5. Can + 87 -2. 015 - 47 -2. 015 - 47 -2. 015 - 67 -2. 015 - 67 -2. 015 - 67	5,828-62 8,745-95 -245-16-02 8,031-03	1.947-87 -7.94-97 -9.97-97	+7.195-93 -1.985-07 7.445-83	TELL THE NO.	-1.10 - 02 -4.00 - 33 -2.341 - 07 -2.041 - 07 -2.041 - 07	*1.*31.*02 *3.*00.*03 *3.*01.*03 *41.51	-3.17 - CP -0.404 - 82 -2.60f - 32	7,925 62 -7,865 06 -1,475-02	1.40F-82 4.40F-82 2.71F-86	1,997-6 1,675-6 2,278-6
#1.942 -#3 #1.944 -#22 -7.444 -#32 -7.444 -#32 #1.444 -#33 -9.237 -#2 3.444 -#3	1:32/-07 3:fit-62 1:4%-02 -2:16f-8: -2:0 M-02 4:172-02 17 up u m 3:104-05 6:546-05	4.471-02 -3.311-42 -1.41-07 -1.41-07 -1.51-07 -1.51-07 -1.51-07	5. Can + 87 - 2. 015 - 47 - 4. 015 - 47 - 4. 017 - 83 - 4. 017 - 83 - 4. 017 - 83 - 4. 017 - 83	9,878-87 8,744-95 -745-16-07 8-011-09	1.94*-82 -7.96 -82 -8.97*-92 -1.91*-85 -9.11* 81	*7.195-93 *5.645-07 7.445-03 *7.195-03 *5.55-07	#84## - 62 24 - 64 - 76 - 74 - 46 - 75 - 74 - 76 - 76 - 74 - 776 - 78 - 74 - 776 - 78 - 74 - 776 - 78	-1.10-02 -4.00 -01 -5.54-07 -5.04-07 -7.04-07	-2, -01 -02 -3, -03 -02 -3, -04 -03 -7, -04 -03 -7, -04 -03	-3.17 - CP -0.604 - 62 -2.604 - 32	7,92F 62 -7,86F-06 -1,47F-02 -7,76F-07 -5,73F-07	1.46F-82 4.40F-92 2.71F-86 3.94F-92 -2.67F-82	1,99F-6 1,07F-6 2,27F-6 -1,49F-8
6.284-03 2.184-02 2.184-02 2.144-03 2.144-03 2.144-03 2.144-03 2.144-03 2.144-03	1,521-07 1,11-62 1,4-02 1,4-16-0 1,0-16-0 1,1-16-0	\$14 88 \$14 88	5. Can +82 -2. 015 - 42 -2. 0 15 - 42 -2. 0 15 - 62 -3. 0 00 - 63 -3. 0 00 - 73 -4. 0 00 - 73 -6. 0 00 - 75	9,828-62 R-748-03 -24516-02 R-218-03 -7-863-83 -7-863-83	1.947-82 -7.96 -87 -9.87-97 -1.819-85 -5.16 81 -7.275-04	+7.164-93 -1.644-92 7.444-93 -1.144-93 -1.144-97 -1.144-97	**************************************	-1.10 - 07 -4.00 - 07 -5.5 - 07 -5.0 - 07 -5.0 - 07 -7.0 - 07 -7.1 - 14 - 07 -7.1 - 14 - 07	-191 - 92 -360 - 97 -360 - 97 -761 - 93 -761 - 93 -761 - 93	-3.17 - CP -6.404 - BP -7.404 - BP -7.404 - BP -7.404 - BP -7.404 - BP	7.92F 62 -7.86F-06 -1.47F-02 -7.76F-07 -5.71F-07 -1.27F-07	1.30F-82 4.40F-92 2.71F-86 3.94F-92 -2.67F-82 2.57F-86	2,278-6 2,278-6 3,278-6
4,942-03 2,184-02 7,244-03 7,246-03 7,246-03 (u, 100 43, 19,24-03 2,04-03 8,06-02 8,06-02	\$1,521-07 \$1,511-02 \$1,411-02 *21,161-02 *21,161-02 \$1,201-03 \$1,201-03 *21,201-03 *21,201-03 *21,201-03	0.071-02 -3.311-02 -3.311-02 -3.31-02 -3.131-02 -3.131-02 -3.131-02 -3.131-02 -3.131-02	7. Car - 87 - 2. Car - 87 - 2. Car - 83 - 2. Car - 75 - 2. Car - 75 - 2. Car - 75 - 3. Car - 75 - 3. Car - 75	5,878-67 R,744-67 P,416-07 R,018-03 -7,183-87 -3,518-05 -6,448-87 -2,745-67	1.44*-82 -7.46 -82 -4.47*-02 -4.41* 81 -4.41* 81 -7.44* 61	+7.144-03 -1.444-02 -2.444-03 -7.144-02 -0.346-03 -0.476-03	**************************************	-1.10+-02 -1.00 -13 -2.20 -13 -2.00 -02 -2.00 -02 -2.00 -02 -2.00 -02 -2.00 -02 -2.00 -02 -2.00 -02 -2.00 -02 -2.00 -02	- 1 21 22. - 2 63 62. - 2 62 63. - 2 64 63. - 63 64 63. - 64 64 63. - 64 64 64.	-3.17-07 -0.60 87 -2.607-32 -7.607-32 -7.847-97 -6.44-07	7.92F 62 -7.86F 06 -1.47F-42 -7.76F-07 -5.71F-87 -1.27F-83	1.30F-87 4.40F-97 7.71F-86 3.54F-87 -2.61F-87 2.57F-87	7,77F-6 -1,49F-6 -1,49F-6 -1,79F-6
######################################	1.92(-0.7 3.711-67 2.09-02 -2.16(-0. -2.08-0.7 4.171-02 17	0.077-02 -1.32-02 -1.34-02 -1.34-02 -1.34-03 -1.34-03 -1.34-03 -1.34-03 -1.34-03	" 1. 69* -87 "2. 615* -87 "2. 615* -83 1. 605 -83 "1. 607 -83 -1.	-/.163 67 -/.16-07 -/.16-07 -/.163 67 -/.163 67 -/.163 67 -/.164 68 -/.164 68	1.44*#2 77.66 -87 4.87*-07 *1.01*#5 -9.11* 61 -7.2**-04 -7.10* 61 -7.10* 61	*2.184-93 *1.885-92 7.449-93 7.196-92 -1.196-93 *1.296-93 -1.198-92	**************************************	-1.10-02 -1.00 -02 -1.00 -02 -1.00 -02 -1.00 -02 -1.10 -02 -1.10 -02 -1.10 -02 -1.10 -02 -1.10 -02	-22102. -30307. -20707. -20707. -30707. -30707. -3782.	-3, 17 - CP -4, c06 - 82 -2, 607 - 32 -7, 67 - 82 -2, 67 - 92 -4, 67 - 92 -4, 67 - 93 -4, 275 - 03 -5, 275 - 03	7.93F 62 -7.86F 66 -5.42F-02 7.76F-07 -5.73F-07 -5.73F-07 -1.22F-07 -0.27F-07	1.94F-87 -2.71F-8h 1.94F-87 -2.67F-82 -2.67F-82 -1.72F-95 -1.72F-95	3,999-6 3,675-6 3,675-6 -1,496-8 -1,256-6 -9,146-6
4.942.03 2.342.02 2.42.03.03 2.42.03.03 2.40	1,92(-0.7 1,0 1,0 -0.7 1,0	# 1077 - 02	9. Con of the Control	*,678 - 67 R,748 - 67 P,7416 - 67 R,211 - 63 *,718 - 67 *,718 - 67	1.44*#2 7.06 -87 4.87*-97 *1.81**85 -4.16 81 -7.10 61 9.431.84 5.03 97	+7.164-93 -1.467-97 7.449-93 -1.141-97 -1.141-97 -1.111-92 -1.111-92	**************************************	-1.10 - 02 -9.00 -71 -7.551 -02 -7.00 -79 23 UF U W 8.644 -22 1.144 -02 4.541 -02 2.541 -02 2.541 -02 2.541 -02 2.541 -02 2.541 -02 2.541 -02	*1. *21. *02 *3. *00 * 97 *2. *01 * 97 *1. *01 * 53 *1. *07 * 02 *1. *07 * 02 *1. *07 * 02 *1. *07 * 02 *1. *17 * 07 *1. *17 * 07 *1	-3.17-07 -0.006-07 -2.607-32 -7.607-32 -2.647-97 -3.44-03 -6.275-07 -1.116-07	7.92F 67 -1.47F-07 -1.47F-07 -5.73F-67 -5.73F-83 -1.27F-83 -6.77F-07 -9.77F-07	1.307-82 4.407-97 7.717-86 3.947-87 -2.475-92 2.528-96 5.781-92 -1.721-92 -5.741-83	2,278-6 -1,494-8 -1,494-8 -1,494-8 -2,284-6 -2,184-6
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4,194-42	1.585-54	16-191.3-	-5.044-47 2.071-97	1,411-62 -1.611-64	3.250-65 -1.416-61	-3,42f-07 2,446-44	-2.458.82	1.3%-66	7-141-03	1.707-43	1.647-03	7.248-84	-1.747-82
5, 34 · 47	1.1 W 8L	2. Jet - 61	V. 198-41	*1.416-3:	2.147-08	1.927-42	-1.13/-01 -1.461-3/	6 711 - 07	-1.841-42 -1.311-42	% [ 19 - A7 % [ 44 - O]	7.90F-81 1.116-03	-9-117-43	******
-4. fel -63	-7.14-42	*1	-1.36# 44	-1.6/4-6/	-1.17-07	*4.541 W/	*3.416.37	0.4.2.4.	*** ***	*4.874.87	3-124-62	2.728-05	-1.91f-62 -8.126-62
4. CM -03	4.571 87	1.14-02	1.07 -07	- 411-61	+1.001 47	-1.211-02	1.116.00	1.74.01	-2-091-02	-1.871-61	1.57-62	2.244-62	-2.400-02
3. 4 ml - 41	1.4 % - 93	1-004-02	-1.447-63	3.744-07	-1-076-07	-1.034-83	3.177-82	·2.4# - 02	-2.252-62	1. 144-81	2.470-02	2.107-07	-1-165-07
1, JN - 02	7.4 M 22	-2.471-44	40-11-01	-4.174 45	9.69-63	1.776-84	-0.461 87	-1 191-77	1.496-02	4. 146 - 41	-8-117-44	-4-995-82	-1.421-42
-1.478-21	*5.94c .44	1.371-02	-1.546-07	4. 116. 42	+7.16E-84	-5.151-07	1.0W 02	8.7 M - 01	-1.411-02	5, 181-41	-1.510-02	4-404-44	3.501-02
5.00E-C1	1.156 -02						+5. J H -81	1.546-07					
Edit alle Ports	25 08 4 64	14 15					Calculate acc.	31 UF UF H	41812				
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4.985-32	4.4 A) ~ 02	4.94 -82	+5.1W-97	-1.676-07	~ 6 . 8 M ~ 62	-1.817-42	#2.4 ft - 84	V. J 21 - D 2	-1.1%-04	-4. 314-82	-1.445-61	-2.417-0/	-9.771-85
-3.544 -5k	-2.47-02	1.340-01	-2.7cf -0?	-1.214-47	-2.547-AZ	1.40f-87	-4.11-62	4.031-02	-1.7-1-01	*2.8 W -47	-3.311-62	-7.845-62	-1.746-81
-211-52	34 - 37 - 42	5 . c #1 · #2	4.048-82	2.489-#3	9.404-87	2.411-42	4.426+43	~ 1. 911 - 32	-8.014-61	2.415-47	4.646-02	1.125-07	4.855-02
4.841-07	5-2 tt - 32	2 - 454 - 85	-1.5 FF - 47	2-171-34	-1.417 02	-1.117-67	1.444-01	-7, + M - # 1	-3.471-42	~2.84f-#2	-2,441-62	2.116-02	1.445-47
\$ - 415-45	-1.311-07	-2-651 -62	3-1-4-84	1.54 47	-3. +24 - 67	-2.344-02	-4.704-67	1.74 -0.	1-12-45	-2.411-02	-2.005-62	4.455-02	4.734-41
+4-427-02 +446-32	*5.907 62	-3.43t-02 -2.471-03	8, 177 - 61 8, 177 - 64	-2.5cP-07 9.551-07	- 7 . 7 <b>97</b> - 0.7 4 . 4 75 - 04	-1.17(-07 -0.01f 01	40.011-07	1.75-02	10-100.0	-4. 247 · 67	3-115-03	1.277-02	-6.186.82
4. *** 02	4.9403	#. #74 - #2	-1.467-97	-2.610-62	1.47-07	-0.010 01 -0.4.5	*1.385-A2 *4.746-42	-4.5187	4.644-42	2,771-02	1.750-02	2,741-02	6.381-42
	4.434 -02	#4 # 78 · <del>#</del> 4	- 44-14 - 47	-21114-42			-3.1% 03	1.171-02	1.174-02	·1.34·W	-3.44-47	1.734-07	-1.476-82
	***************************************						*****	1.11.11.42					
CALLERY PAIL	26 09 3 84	43425					Cec 160 93.	12 UF U #					
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-7.631-67	4.316-03	7.811 -02	2. 540-02	4. SM - 27	1.617-64	-4.147-87	1.434-42	2.945-64	-1.002-01	-5,204-82	7.144-82	-7.418-05	-7.5~7-02
-2.475-82	-4-3 W - #3	1.4.1-27	2.281.42	4.575-45	· 2 . 7 69 -4 2	-1.64 -#2	1.176-42	·2.74-#1	2.071-62	-7.#77-41	-9.995-89	7.447-81	-2.011-07
8.764 43	-2.5 <b>9</b> 2 -92	-4.446 02	->. \$ \$\$ - 4\$	-1.4#7.67	1.17 64	2.471-82	# 63d - 3 s	4.416-#7	1024-62	- 1. 444 - 47	-7.001-03	î. ê 1 î - <b>ệ</b> u	7,434-42
3.441.45	*** M - 87	20 104 05	2. 1 M - ML	-2.845 P2 -5.185-82	5-444-53	1.965 48	1.441-22	-1.74 -01	*6.4 M *W	+5. 154-B7	1.IM-62	7.0 IL-05	2.476-87
1.810-04 3.7W-67	1.44.02	-1.941-#1 -1.941-#2	2.04F-02	7.151-07	1.044-03	-2.048-#2 -3.252-82	*2.50f *\$4	-1.444-07	-1.00: 07	-1. 2"4-07	5.141-87	1.196-07	3-#86-03
11.461-02	2.726-02	-1.101-82	7. 07 - 04 -7. 7st - 07	\$ . \$ 31 - <b>6</b> 4	4.741-87	1.475-47	4.328-41	1.101-67	144 -02	-1.34F-84	~2.26+-67 5.284-65	-2.184-02	**************************************
-c./st-62	7.034-44	8.6/1-25	-1.54 07	741-47	9.31/-63	58-120.4-	7.454-01	-1.782-01	*1.94(*92	-1.04-07	-5.447-67	2.275-84	1.540-07
2.6.9662	-1.551 83	4.0.5.25	*1. YH U/	7.107-47	74 711 - 93	*******	-6.130-02	7.616-03	-8.4%-45	84 3 14 - 03	~ > . <del>*** * **</del>	4.3/6-44	4.411-88
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1.921-82 4.986-83		3.5mc - 42 4.4% - 41	5. 8 H - F1 1.1 H - 87	-2.202-67	1.241-42	4.457-57	-5.847-62	-5.6 M - 96	5.901-82	7, 1 N - 82	1-07-63	7-857-86	-5.427-45
0.921-02 0.900-03	-1.147-82 -6.141-02 1.341-07	3,544 - 42 9,971 - 98 3,971 - 42	1.3 M - 97 1. 31f - 97	1.247-87	1.244-82 -1.141-84	4,457-57	-5.547-62 -1.171-02	-5.4 M-44 -5.416-02	5.901-82 5.211-01	- 5- 11F - AP	-1.795-84	3.334-02	-1.771-81
4.921-82 4.986-83 -6.181-82 24.49f-22	*8.147-92 *6.141-92 16.146-97 2.575-97	3.504.02 n.nfi.08 3.nm.02 1.18 (8)	1.1 bt - 87 1. 31f - 67 4. 61f - 67	+2.248+62 4.248+82 +5.4×6-02	1,241-82 -1,141-84 -7,451-82	4,457-59   1447-67   1487-67	-5.635-62 -5.171-02 3.5.1-82	-5.6 % - 96 -5.7 K - 92 1.1 W - 01	5,931-82 5,211-03 1,146-05	+ 5- 117 - A7 +1, 1W - 84	-1.791-84 1.147-84	3.55e-02	-1.776-61 -1.716-64
4.921-82 4.985-83 -6.381-82 24.49-92 -5.413-32	*8.147-82 *8.141-82 *6-118.1 *8-118.1 *4-18-67	3.5%+ uz n.nfz-qt 2.09-02 1.12-03 -2.46-81	1.5 M - 97 - 11.5 M - 11.5 M - 12.4 M - 97	+2.242-62 4.447-82 -5.471-62 4.481-63	\$ ,244 -82 -3, 141 -84 -3,454 -82 +2,131 -32	4,457-53 Line/-#2 Litef-62 Litef-62	-5.547-62 -1.171-02	-5.4 M-44 -5.416-02	5.901-82 5.211-01	- 5- 11F - AP	-1.795-84	3,397-02 -4.157-07 1.117-02	-1.771-81
#. #21-#2 #. ##6-#3 ##. ## - #2 #### - #3 #### - #3 #### - #3	-1.147-92 -0.141-07 1.517-07 2.925-07 1.170-07	3.544.42 n.nf08 3.69.42 1.13.63 n3.66.83	- 1.4 M - 97 - 1.5 M - 97 - 1.4 M - 97 - 1.4 M - 97	-2.242-62 4.447-82 -5.447-62 4.447-63 4.447-63	\$ ,244 -82 -3,141 84 -7,454 -82 -2,171 -32 9,111 -82	4,457-99 [.447-67 [.147-67 [.441-97 4,441-92	*5.427 *62 *5.471 *62 3.412 *44 4.572 *36 *5.42* *31	-5.6 %-46 -5.915-U2 -5.1 w -0* -[.J ;8-0* -8.0 % -5*	\$,931~82 0-113.6 0-21,1 18-30-6	- 5- 117-07 -1, 7M-00 3-627-63 3-658-81	-1.79f-86 1.1eF-86 -5.45f-81	3.33e-02 -4.15f-07	-1.776-81 -1.716-84
8.921-82 -0.981-82 -0.181-82 -0.981-32 -0.911-32 -0.911-32	-3.147-32 -0.131-37 2.317-37 2.375-47 3.130-07 4.386-07	3.50c oz nentent 3.600 oz 1.75 oz nentent nu oz	2.3 84 - 87 2. 224 - 67 4. 624 - 67 - 2. 4 74 - 67 - 4. 841 - 17 4. 244 - 43	**************************************	t.249 -82 -3.141 -84 -3.454 -82 -2.454 -82 9.411 -82 9.456 -83	4,45P-92 1,44'-87 1,14F-02 1,44F-02 -4,441-87 5,17F-87	*5.***********************************	-5.6 %-96 -5.7 16-02 -1.3 67-03 -1.3 67-03 -1.3 68-13 -1.3 72-13 -1.27-04	5,432.482 5,412-03 1,145-04 -3,312-45 7,145-64 3,312-45	- 5. 117 - 62 - 1, 256 - 84 5. 627 - 62 5. 650 - 61 - 9. 617 - 61 5. 630 - 61	*1.74 -06  .167 -06  -5,455-43  -5,421-62  3,115-62  1,541-06	3,537-02 -6,15f-67 -1,14f-62 -7,14f-64 -9,64f-63	-1.72f-61 -1.71f-64 1.94f-94 -1.31f-02 5.67f-81 -1.3M-01
8.025-87 0.005-83 0.05-84 0.26-37 0.05-33 0.05-32 0.05-32	-9-4 ct -9-2 	3.544.42 n.nf08 3.69.42 1.13.63 n3.66.83	- 1.4 M - 97 - 1.5 M - 97 - 1.4 M - 97 - 1.4 M - 97	-2.242-62 4.447-82 -5.447-62 4.447-63 4.447-63	\$ ,244 -82 -3,141 84 -7,454 -82 -2,171 -32 9,111 -82	4,457-99 [.447-67 [.147-67 [.441-97 4,441-92	*5. 6 47 * 6 4 *7. 6 75 * 6 4 5. 6 75 * 6 4 6. 6 75 * 6 6 4. 6 75 * 6 6 *5. 6 75 * 75 5. 6 75 * 75 *6. 6 75 * 6 6	-5.4%-96 -5.4%-07 -6.4%-09 -5.4%-09 -5.4%-09 -5.4%-96	5,902-82 5,412-03 1,196-05 -3,96-85 -3,316-82 7,196-84	- 5- 117-07 -1, 7M-00 3-627-63 3-658-81	-1.74 -06 1.16F -86 -5,45F-83 -5,45F-62	3,137-02 -8,15f-87 -1,14f-82 -1,14f-82	-9.776-88 -8.716-84 1.916-84 -3.116-92 5.676-83
8.921-82 -0.981-82 -0.181-82 -0.981-32 -0.911-32 -0.911-32	-3.147-32 -0.131-37 2.317-37 2.375-47 3.130-07 4.386-07	3.50c oz nentent 3.600 oz 1.75 oz nentent nu oz	2.3 84 - 87 2. 224 - 67 4. 624 - 67 - 2. 4 74 - 67 - 4. 841 - 17 4. 244 - 43	**************************************	t.249 -82 -3.141 -84 -3.454 -82 -2.454 -82 9.411 -82 9.456 -83	4,45P-92 1,44'-87 1,14F-02 1,44F-02 -4,441-87 5,17F-87	*5.***********************************	-5.6 % - 46 -5.7 16 - 07 -1.3 67 - 03 -1.3 67 - 13 -1.3 67 - 13 -1.3 16 - 13 -1.3 16 - 13	5,432.482 5,412-03 1,145-04 -3,312-45 7,145-64 3,312-45	- 5. 117 - 62 - 1, 256 - 84 5. 627 - 62 5. 650 - 61 - 9. 617 - 61 5. 630 - 61	*1.74 -06  .167 -06  -5,455-43  -5,421-62  3,115-62  1,541-06	3,537-02 -6,15f-67 -1,14f-62 -7,14f-64 -9,64f-63	-1.72f-61 -1.71f-64 1.94f-94 -1.31f-02 5.67f-81 -1.3M-01
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9.921-82 9.980-83 -0.181-82 9.491-92 9.491-32 5.401-32 9.461-82 4.481-82 4.481-82	**************************************	3.504.02 8.07.02 2.09.02 5.32.02 5.32.03 7.00.02 5.54.03 4.74.00	2.3 84 - 87 2. 224 - 67 4. 624 - 67 - 2. 4 74 - 67 - 4. 841 - 17 4. 244 - 43	**************************************	t.249 -82 -3.141 -84 -3.454 -82 -2.454 -82 3.411 -82 W.446 -83	4,45P-92 1,44'-87 1,14F-02 1,44F-02 -4,441-87 5,17F-87	*5.607 *62 *5.671 *62 3.612 *63 4.672 *66 *5.675 *66 *5.675 *67 *6.173 *66 *7.144 *62	-3.6 %- 46 -5.9 [ ~ U2 -1. U ~ 0 -[. J £* 04 -[. J £* 04 -1. 0 %- 14 -1. 0 %-	5,92:482 5,411-03 8,141-09 43,981-85 -3,511-44 5,191-84 5-211-45 5,411-45	- 5. 117 - 62 - 1, 256 - 84 5. 627 - 62 5. 650 - 61 - 9. 617 - 61 5. 630 - 61	-1.74 -06 1.16-06 -5.45-43 -5.42-62 3.11-62 1.14-06	3,537-02 -6,15f-67 -1,14f-62 -7,14f-64 -9,64f-63	-1.726-81 -1.716-84 1.946-84 -3.316-92 5.676-83 -3.38-93
#1.925-82 #1.985-83 #0.185-84 #1.981-92 #1.951-32 #1.961-32 #1.961-32 #1.961-92 #1.961-92	-9-4 ct -9-2 	3.504.02 8.07.02 2.09.02 5.32.02 5.32.03 7.00.02 5.54.03 4.74.00	2.3 84 - 87 2. 224 - 67 4. 624 - 67 - 2. 4 74 - 67 - 4. 841 - 17 4. 244 - 43	**************************************	t.249 -82 -3.141 -84 -3.454 -82 -2.454 -82 3.411 -82 W.446 -83	4,45P-92 1,44'-87 1,14F-02 1,44F-02 -4,441-87 5,17F-87	*5. 6 47 * 6 4 *7. 6 75 * 6 4 5. 6 75 * 6 4 6. 6 75 * 6 6 4. 6 75 * 6 6 *5. 6 75 * 75 5. 6 75 * 75 *6. 6 75 * 6 6	-5.4%-96 -5.4%-07 -6.4%-09 -5.4%-09 -5.4%-09 -5.4%-96	5,92:482 5,411-03 8,141-09 43,981-85 -3,511-44 5,191-84 5-211-45 5,411-45	- 5. 117 - 62 - 1, 256 - 84 5. 627 - 62 5. 650 - 61 - 9. 617 - 61 5. 630 - 61	-1.74 -06 1.16-06 -5.45-43 -5.42-62 3.11-62 1.14-06	3,537-02 -6,15f-67 -1,14f-62 -7,14f-64 -9,64f-63	-1.72f-61 -1.71f-64 1.94f-94 -1.31f-02 5.67f-81 -1.3M-01
5.921-82 0.981-83 0.281-82 2.491-92 5.011-32 0.411-32 0.411-82 6.011-82	-9.4 a7 -9e -19.5 a3 b1 -97 a3 b1 -97 a1 79 -97 b2 3M 37 b2 5M 47	3.50c+ 02 1.071-02 2.091-02 132-02 2.000-02 -2.000-02 -3.50-02 -0.Fas @a	3-130-92 2-21-92 4-22-92 -3-45-92 -3-45-92 -4-34-93 2-40-93	-2.242-62 6.247-82 -5.4 51-02 6.451-62 -6.151-82 -7.530-82	\$,249.42 ~3,541.40 ~2,649.42 ~2,519.42 %,519.42 %,649.83 ~2,549.82	をいるとからう そのもできまします。他と もしものできまったのできまったのできまったのできる。 ちょうできると こともは、他と こともは、他と まったようできままた。	** ** ** ** ** ** ** ** ** ** ** ** **	-3.6 %- 46 -5.9 [ ~ U2 -1. U ~ 0 -[. J £* 04 -[. J £* 04 -1. 0 %- 14 -1. 0 %-	5, 902 - 82 5, 412 - 03 8, 197 - 00 93, 932 - 85 - 3, 332 - 82 F, 194 - 84 5, 24 - 92 - 2, 924 - 82 4 F C C C	-5. 117-62 -1. 256-62 -1. 59-62 5. 657-63 -9. 667-63 5. 628-63 7. 157-62	-1.79 - 86 1.67 - 85 -5.92 - 82 -5.92 - 62 3.55 - 62 -5.90 - 82	3,39-62 -46,25-67 5-17-62 -7,14-62 1,465-64 -9,846-63 -8,156-66	-9.726-88 -1.716-68 1.946-69 -3.216-92 5.616-82 -9.216-92 9.916-92
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5.921-92 0.901-93 0.381-32 3.411-32 5.411-32 5.411-32 5.411-92 4.411-94 6.411-	#3.1.21-32 ************************************	3.5 sec - a2 sec / ft - a2 sec / ft - a2 sec / a	1130 - 97 10-217 -	12-48-69 14-49-69 14-	\$1,289-02 -1,161-06 -1,464-62 -1,111-62 -1,111-62 -1,111-62 -1,111-02	\$1047-02 \$1447-02 \$1447-02 \$1447-02 \$1441-02 \$1441-02 \$1447-02 \$147-02 \$1447-0	**************************************	-5,6 %-56 -5,7 %-96 -5,7 %-97 -1,1 \$1-00 -1,1 \$1-0	# 100 - 82 5 - 21 - 03 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0	-5, 17 - 67 -1, 7W - 56 -5, 67 - 62 -5, 67 - 62 -5, 67 - 62 -5, 67 - 62 -5, 52 - 52 -5, 60 - 62 -6, 7W - 62 -1, 10	-1.741-0. 1.447-0. -5.457-0. -5.457-0. 1.507-0. 1.507-0. -1.507-0. -1.607-0. -1.	**************************************	-0.726-05 -0.716-04 -1.016-04 -1.016-02 -0.76-07
2. 22 - 62 0. 36 - 63 0. 36 - 53 0. 36 - 53 0. 40 - 72 0. 61 - 72 0. 61 - 72 0. 61 - 72 0. 61 - 73 0. 71	#3.4 (2 - 32 - 44.54 - 32 - 4.54 - 4.54 -	3.5 sec - u2 n=16 = 02 2.5 nm - 02 2.5 nm - 02 1.78 = 02 - u2. nm - 02 3.5 nm - 02 - u. nm - 02 - u. 12 =	1130-07 1031-07 1040-07		\$,249-62 -1,14-62 -2,44-62 -2,14-62 -2,14-62 -2,14-62 -2,14-2 -2,14-2 -3,14-2 -4,14-2	8.047-02 1.047-02 1.047-02 1.041-	-50 of -6.2 -5.131-02 3-0.1-02 4.712-03 -5.12-03 -5.42-03 -5.42-03 -6.13-03	-5.6 M-96 -5.7 M-96 -5.7 M-97 -1.2 M-97 -1.2 M-97 -1.2 M-97 -1.3 M-97 -1.4 M	5-02-02 5-41-01 1-1-0-05 -2-04-05 -3-31-0-05 -3-31-0-02	-5, 17 -67 -6, 27 -62 5, 65 -61 5, 65 -61 5, 67 -62 5, 67 -62 5, 70 -62 1, 10 -67 1, 10 -67 1, 10 -67 -1, 10 -67 -1	-1.249-0. 1.447-0. -1.427-0. -1.427-0. 1.517-0. -1.427-0. 1.427-0. -1.047-0. -1.047-0. -1.047-0. -1.047-0. -1.047-0. -1.047-0. -1.047-0. -1.047-0. -1.047-0.	1.59-02 -0.151-02 -1.14-02 -1.44-03 -1.58-03 -1.58-03 -1.58-07 -1.58-02 -1.58-02 -1.58-02 -1.58-02 -1.58-02 -1.68-07 -1.68-07 -1.68-07 -1.78-02 -1.78-02	-9,22-85 -1,216-86 -1,316-92 -1,316-92 -1,316-92 -1,169-
2.921-92 9.981-93 9.291-92 9.491-92 9.491-92 9.491-92 9.491-92 9.491-92 6.491-92 6.491-93 6.491-93 6.491-93 6.491-93 6.491-93 6.411-	-9.4 at -92 -0.54 bt -92 -0.54 bt -92 -0.52 -02 -0.52 -02 -0.52 -02 -0.53 -02 -0.54 -0	3.5 sec - u2 n=16 = 02 2.5 n= 162 2.5 n= 162 - 2.5 n= 62 - 2.5 n= 62 - 3.5 n=	1130 - 97 10-217 -		\$,249-62 -1,141-62 -2,441-62 -2,141-62 -2,141-62 -2,141-62 -2,141-62 -4,141-62 -4,141-62 -4,141-62 -1,141-	8.047-02 1.047-02 2.047-02 -0.041-02 -0.041-02 -0.041-02 -0.041-02 -0.041-02 -0.041-02 -0.041-02 -0.041-02 -0.041-02 -0.041-02 -0.041-02 -0.041-02 -0.041-02 -0.041-02 -0.041-02 -0.041-02 -0.041-02 -0.041-02 -0.041-02	#5.60 of 102   #1.171 - 02   #1.171 - 03   #1.171 - 03   #1.171 - 04   #1.171 - 04   #1.171 - 05   #	-5,6 %-56 -5,716-02 v.1 w -0- -1,11-00 -1,01 v.0- -1,01 v.0-	# 100 - 82 5 - 21 - 03 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0	-5, 17 - 67 -1, 7W - 56 3, 67 - 67 3, 67 - 67 3, 67 - 67 3, 67 - 67 3, 60 - 67 3, 60 - 67 -1, 10 - 67	-1.741-0. 1.447-0. 1.447-05.437-0. 1.517-0. 1.517-0. 1.517-0. 1.447-0. 1		-1,724-81 1-,716-84 1-,716-84 1-,116-92 5-,176-82 5-,176-82 5-,176-82 5-,176-82 5-,176-82 5-,176-82 7-1,916-82
2. 22 - 62 0. 36 - 63 0. 36 - 53 0. 36 - 53 0. 40 - 72 0. 61 - 72 0. 61 - 72 0. 61 - 72 0. 61 - 73 0. 71	#3.1.21-32 ************************************	3.5 sec - a2 sec / ft - a2 sec / ft - a2 sec / a	1130-07 1031-07 1040-07	12-48-02 14-48-02 14-48-02 14-48-02 14-48-02 14-48-02 14-48-02 14-29-42 14-	\$1,249-62 -1,141-64 -1,441-62 -1,411-62	8,457-02 1,447-	-50 of -6.2 -5.131-02 3-0.1-02 4.712-03 -5.12-03 -5.42-03 -5.42-03 -6.13-03	-5.6 M-96 -5.7 M-96 -5.7 M-97 -1.2 M-97 -1.2 M-97 -1.2 M-97 -1.3 M-97 -1.4 M	######################################	-5, 17 -67 -6, 27 -62 5, 65 -61 5, 65 -61 5, 67 -62 5, 67 -62 5, 70 -62 1, 10 -67 1, 10 -67 1, 10 -67 -1, 10 -67 -1	-1.249-0. 1.447-0. -1.427-0. -1.427-0. 1.517-0. -1.427-0. 1.427-0. -1.047-0. -1.047-0. -1.047-0. -1.047-0. -1.047-0. -1.047-0. -1.047-0. -1.047-0. -1.047-0.	1.59-02 -0.151-02 -1.14-02 -1.44-03 -1.58-03 -1.58-03 -1.58-07 -1.58-02 -1.58-02 -1.58-02 -1.58-02 -1.58-02 -1.68-07 -1.68-07 -1.68-07 -1.78-02 -1.78-02	-9,22-85 -1,216-86 -1,316-92 -1,316-92 -1,316-92 -1,169-

APPENDIX B

Continued

CALVER NO. TO OF J BASELS

COLUMN WS.	PH 127 W MATE						the part was	45 OL 1 M	4 1 M 7 E				
40-14.6-		3.472-84	1,484-85	4.894-78	-4. \$19 -43	4.646-47	1.TH 92	******	-1.+4-67	-1.112-07	-1.144-01	4.11-95	9.496-93
4 - 149 - 12 		3.74-61 -	-1, 979 - 69 -4, 6^4 - 83	-2.044.87 4.874-81	4. 518-42 4. 518-42	1,544- <b>67</b> 4,971-11	9.191-67 -4.211-92	7.74e-41 14.6 M - 42	~}.45{ ~}} ~&.{}}	1,451-47 2,481-77	-1-01/-01	-1,147-87 -7,117-97	\$.476~8" 5.795~87
-4-211-03	-3.475-07	\$+#12 ## · ·	-4, Ise - 81	5 . 3 PV - B P	-1,471-47	+1.784-67	-1. 141 21	4.14-81	3,731-#2	8. 847 GJ	-4.8 F-21	4.545-82	-5.725-41
8.754-85	-:.?# - \$4	1.621-92	3,177-92	-6, 196-99	1.1 11-47	*****	h . 1 20 - 87	5.74.92	-0-541-07	4- 164 - 05		-1.914-47	7-854-P.
1.011-07		1.47 W -	8, 47F - \$5	-1.5 6-87	**************************************	5.835 as 6.665-es	*1.174-87 *1.144-87	1.544-07	548-47 +5-114-81	+ 5, 7+5-84 + 7, 5+6-85	-1.547-67 7.748-65	1.564-07	1.777-47 5.447-83
-4-5 R - 63	-4.7M - 61 -	9.17 67	1.14-6	-4.714 -67	1.010-01	** . FYE-&7	3 17 - 4.1	. 5. 14: -84	3-016-04	- L. S N - 8.1	1-107-17	7.618-65	-1.211-47
4-151-02	44.2 M - 92	**					1 . 4 of -82	-3-644-63		•••			
Can plat the	47 AF 4 NETA	35					Suigness Tub	-1 OL 4 KI	17862				
1.44-97	3.580 -07	1.841-85 -	·/. + /1 - 4/	2.115-87	-4.44-42	\$ . TOE -4 B	10-101-02	**********	***18 - 02	- 2. 456 - 47	-1.4W-07	4.714-81	-1.574-03
*2.741-47	1.49:47	9-149-44 +	- 1. J 10 - AF	4.1 16 - 67	-1.7m-49	1.140-07	+ b + 744 - 6V	1.54-41	-4-144-45	4.424.42	·*. 941 - 27	7.481-47	-9.1 <del>11-</del> 63
4.+H-W		3.044-07 3.044-07	4, 133-83 4, 889-82	2.306-83 3.584-82	1.74-61	2.154.92 -1.116.01	4.046 47 1.417 67	-3-1 54-04	**************************************	14. W. 15	1,491-87	4.79-05 1.4M-41	*3.44F-#2 3.424-#2
-1.616-91			4. 494 197	4. *** . **	-1.318-67	-3.4W-41	6.abl -62	3.14-64	3-996-03	1. 1 14 -81	2. 141 -42	+1.271-61	-4.055-07
4-14-84	8.64 47 .		4. 14 - 47	4.64 61	1-314-67	4.464.83	+1.144-63	· 2. C M - 42	+2.311-01	+3.11F #2	4- 44F - 84	-7.434-67	-1-3 M - # #
4.44.4.61		\$ 446-47 2,114-47	8,314 A4 10,14 (1)	3,4M 47 3,4M 47	1.54.61	-5,435-92 -4,145-92	4,341.61	1,001 +42	1.362.43 +4.332.44	9. 829 - 81	1.141.0J	7.136-61 7.136-62	1.544-42
9.142-07	-1.3 86 87	11100-01	4,0				4-411-02		*****	44111-64		4 2 1 24	
the same are	SE OF W MATE	***					CON JUNE MICH	++ CF W RI	1014				
~#-+ <del>++</del> +	-1.54 - 34	4.343-41	4,479 -47	~ <b>4.</b> 4n4 +84	8 . Bar- 04	3,845-07	-1.141-#2	4.514 -62	- 5, 141- 42	4 4M -41	-7" # AL - 8%		-9.116-02
*** * 10 -42	-6.21 -42 4.10-42	5. P01 - P2 -	2, 2 10 · 67 2, 2 ** - 5;	- 8 a 7.50 - 804 	\$ . \$ 4.8 · 46.5 \$ . 40 10 · 444	*2. c 14-63	4.581-81 -1.531-81	58-11-62	* 5+ *% -#2 4+ 815 -#3	-/, em-4) -/, em-4)	**************************************	-3.410-07 -7.710-04	->.652-#2 1.817-#3
14-14 tun 14-14 tun	2.534.52		- 4. 300 - 42	-2.007-92	4. 501-41	* 1 . 447 - 43	2.54-43	4. B K - 42	4.44.44	+1. 167-83	+1.474-57	-7.7 <i>0</i> 7-02	on liteba
4.14: 24	3.045 . #2 .	Se # Se + #3	2.445 45	4.145-42	4.607-93	1.714-87	4.14-34	- 5.594 -61	.4.114.41	14. 24P.4+	-1-981-62	4.704-63	-7.810-47
-4-239-42			* * * SF - CA	4.735-64	44.4W -01	14-1214	-114-42	7.5 M - 9.0	4. 34. 44	3, 111-14	***************	\$. 40#~#? -2. #1*+ 6.	-1 49°-42 -1.44°-62
44 JW A7 2-798 40		2.015-07 + 4.50k-31	147-47 24554-41	1.34.4	4.17-47	-1.404.45	**************************************	4.1.1.4.4.4.4.4.4.4.4.4.4.4.4.4.4.4.4.4	-3.4nt-31	+ 6, 5 M - 97 9, 774 - 97	- 3,417-47	7.547.46	-2-212-23
-J. FW 41	* . 4 44 - 41		****	*****		*****	4.121.46	********					
Lak office to.	P# 48 12 #48 **	1#					Kanama Mil	** ** ***	118 EK				
2.44-81	*#+# be - #2	7.44-17	¿. • ₩~ ¢1	2.017-01	4.196-82	2,44C-P3		45 # 4 M	1185K 6+3M+84	1.54.42	4.045-47	1,44f- <b>0</b> 6	+3.616-63
4 - 4 4 - 44 4 - 4 7 - 4 5	**** be - 62	2.44.12 1.44.12		4.541-27		1.446.47	76.2 M 182	-3-0 W -3-6 -4-14-6-6-	(+2%-82 -3.431-82	1.040.27	-1.079-84	-1W-63	1-176-67
4.44.46 4.47.48 7.44.47	16 - 34 64 67 16 - 44 64 67 10 - 44 64	2.44-22 1.44-22 1.74-2.	· 7 . \$51 • \$1 • 3, 447 • \$2	4.447-83 -4.847-83 1.1W-82	19-14-1	1.040.41	*6.244 *84 **6.244 *84 4.644 *84	-2.0 M(+)04 +2.6 M(+)04 +1.6 M(+)04	4.3M-87 -3.431-87 4.374-82	3.0W+37	44-11-44	-1,-16-67 -2,446-46	10-16-01
2.84(-82 4.07(-81 -0.16(-82 -0.26(-82 -0.26(-82	**** \$6 * \$6 ************************************	2.44-22 1.44-22 2.74-2 3.47-2 -	, 7, 651 - 84 - 5, 647 - 67 - 9, 791 - 87 - 5, 146 - 87	4.464-83 4.864-83 8.244-42 4.646-42	19-14-61 19-14-61 14-14-61	9,446-47 -0,446-47 4,745-47 -2,316-63	76.2 M 182	-2.0 MT+34 +2.6 M+34 +1.6 M+92 +0.7 M+92	4.34.47 -3.431-47 4.371-42 4.441-02	1.040+37 -5.217+47 -7.407-63	++++++++++++++++++++++++++++++++++++++	-1,-16-67 -2,046-46 -3,516-63 -2,678-63	\$4-36-49 \$4-36-40 \$4-750-40 \$4-455-40
2-44-46 2-17-65 	"#1# 00 - #2 - 000 - #2 #10 15 - 03 #1 18 10 - 03 0.3 15 - 03 0.5 10 - 62	#. 444 - 9# 1, 454 - 9# 4, 254 - 9# 3, 454 - 9# 4, 454 - 9# 4, 454 - 9#	1, 11 - 11 1, 141 - 67 1, 141 - 67 1, 146 - 67 1, 121 - 67	45,469-63 44,664-63 44,664-63 44,566-64 41,566-61	\$40-46-6 \$2-\$46-6 \$4-\$40-5 \$4-\$40-5	1, 46, 47 -4, 46, 47 -2, 46, 48 5, 49, 48	# 1 00 - 02 # 2 - 030 - 03 # 2 030 - 03 # 2 030 - 03 # 2 030 - 03	-2.0 Mm/s -2.0 Mm/s	6,234 - 82 - 3,431 - 82 - 4,471 - 82 - 4,471 - 83 - 4,771 - 83 - 2,771 - 83	1.040-27 -5.217-47 -7.247-63 -8.871-67 -1.141-46	10-11-4 10-11-4 10-110-4 10-110-1 10-11-1	-1,-16-67 -2,016-66 6,516-63 -2,078-63 -1,506-63	\$4-9\$c.6 \$6-36;40 \$4-76,40 \$4-816,50 \$6-816,50
4.44 - 44 4.47 - 65 -5.46 - 67 -9.46 - 67 -9.76 - 58 -9.76 - 58 -9.76 - 68	***** *** ****************************	\$.444 - \$2 \$.454 - \$2 \$.454 - \$2 \$.454 - \$2 \$.455 - \$2	1,151-01 1,041-07 1,041-07 1,146-07 1,146-07 1,146-07	4.464-83 4.864-83 8.244-42 4.646-42	19-14-61 19-14-61 14-14-61	9,446-47 -0,446-47 4,745-47 -2,316-63	**************************************	-2.6 18 -34 -2.6 36 -92 -2.6 36 -92 -3.7 46 -92 -3.6 5.7 42 -3.7 47 -92	6.2% ## -3.431-42 #.474-42 8.44-03 -3.79-33 J. Pd44	1.040-37 -9.217-47 -7.40-63 -871-67 -1.47-46	-1.07-84 4.417-47 -4.644-67 4.064-61 1.17-67 -7.424-64	10-11-07 08-11-11-1 10-11-1-1 10-11-1 10-10-1	48-9944 18-1624 18-1624 18-1824 18-1824 18-1824
2-44-46 2-17-65 	***** \$ \$ \$ \$ \$ \$ \$ \$ \$ \$ \$ \$ \$ \$ \$ \$ \$	#. 444 - 9# 1, 454 - 9# 4, 254 - 9# 3, 454 - 9# 4, 454 - 9# 4, 454 - 9#	1, 11 - 11 1, 141 - 67 1, 141 - 67 1, 146 - 67 1, 121 - 67	4.44-69 -4.64-63 1.270-67 -4.500-63 -1.500-61 1.641-61	2 - 540 - 45 10 - 540 - 57 12 - 670 - 55 12 - 670 - 45 12 - 740 - 41	9,446-86 -0,840-06 4,746-47 -2,196-83 9,478-98 5,446-83	# 1 00 - 02 # 2 - 030 - 03 # 2 030 - 03 # 2 030 - 03 # 2 030 - 03	-2.0 Mm/s -2.0 Mm/s	6,234 - 82 - 3,431 - 82 - 4,471 - 82 - 4,471 - 83 - 4,771 - 83 - 2,771 - 83	1.040-27 -5.217-47 -7.247-63 -8.871-67 -1.141-46	10-11-4 10-11-4 10-110-4 10-110-1 10-11-1	-1,-16-67 -2,016-66 6,516-63 -2,078-63 -1,506-63	\$4-9\$c.6 \$6-36;40 \$4-76,40 \$4-816,50 \$6-816,50
# - 9 m - me # - m 7 m - 6 m - m - m - 6 m - m - m - m - m - - m - - m - m - - m -	**************************************	\$.444 - \$2 \$.454 - \$2 \$.454 - \$2 \$.454 - \$2 \$.455 - \$2	1,151-01 1,041-07 1,041-07 1,146-07 1,146-07 1,146-07	4.44-69 -4.64-63 1.270-67 -4.500-63 -1.500-61 1.641-61	2 - 540 - 45 10 - 540 - 57 12 - 670 - 55 12 - 670 - 45 12 - 740 - 41	9,446-86 -0,840-06 4,746-47 -2,196-83 9,478-98 5,446-83	10 - 100 - 24 	-2-01820 -2-01826 -2-019-02 -2-018-02 	6.2% ## -3.431-42 #.474-42 8.44-03 -3.79-33 J. Pd44	1.040-37 -9.217-47 -7.40-63 -871-67 -1.47-46	-1.07-84 4.417-47 -4.644-67 4.064-61 1.17-67 -7.424-64	10-11-07 08-11-11-1 10-11-1-1 10-11-1 10-10-1	40-14:40 40-14:40 40-14:40 40-14:40
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# # # - ## # - 172 - # 8 8 - 170 - 184 - # 8 8 - 180 - 184 - 183 - 184 - 18		2.466 - 22 5.466 - 22 7.270 - 20 2.471 - 27 3.487 - 27 3.487 - 25 3.487	- 7. \$13 - 84 - 9. \$13 - 82 - 9. 59 - 82 - 5. 246-82 - 5. 276-82 - 5. 246-84 - 7. \$40-84	をよりながっぱき マル、エルサースを えって かい 中文 マル、ちがといれた ・ちょうかか・様と ド、ホルド・ベト マル、エア・ベト	· 是,在 · 使用 · 是,在 · 使用 · 是,在 · 使用 · 是,在 · 使, · 是, 在 · 使,	6.446.46 4.246.46 4.246.46 -2.456.46 5.456.46 5.456.46 5.456.46 5.466.46	**************************************	一次。每個十分的 中方、每個一個名 中方、每個一個名 中方、中面、一個名 中方、一一一 中方、一一 中方、一一 中方、一一 中方、一一 中方、一一 中方、一一 中方、一一 中方、一一 中方、一一 中方、一一 中方、一一 中方 一一 一一 中方 一一 一一 一一 一一 一一 一一 一一 一一 一一 一一	E.236 - PJ - 7.421 - 92 - 6.914 - 92 - 6.914 - 93 - 6.439 - 93 - 74 - 93 - 74 - 94 - 74 - 94 - 74 - 94	\$.040.27 -5.217-02 -8.24-03 -8.24-03 -8.24-04 -5.47-04 -5.47-04 -5.47-06	** 1	-1,-1807 -2,-19903 -3,-5103 -2,-51-03 -3,-6003 -3,-6003 -3,-6003	\$15 \$15 - 48 \$15 - 48 \$20 - 48 \$20 - 48
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APPENDIX B - Continued

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**************************************	5-79-92	1,28	\$1,200-03	# 1
**************************************	8-78-82	1,200 eg/	\$1,200-03	# 1
**************************************	8-78-82	1,284-62	\$1,200-03	# 1
**************************************	8-78-82	1,286-82	\$1,200-03	# 1
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**************************************	8.78.82	1,284-62	\$1,200-03	# 1
**************************************	10   10   10   10   10   10   10   10	1,284-82	\$1,200-03	# 1

## APPENDIX C

## EIGENVECTOR DIAGRAMS

This appendix contains schematic representations of the first 16 modes of the thin mirror (figs. C1 to C10). For each of these modes the mirror deflection along the Z-axis at each grid point is written beside that grid point. The contour lines indicate the nodes of each mode. Note that mode 3 is a bowl-shaped mode and therefore has no node line. The numbers at the grid points are taken directly from appendix B, columns 1 to 10 inclusive, and are displayed in this manner to provide more insight into actual shapes than can be obtained from looking at columns of numbers. Each number has been multiplied by 190 for scaling purposes.

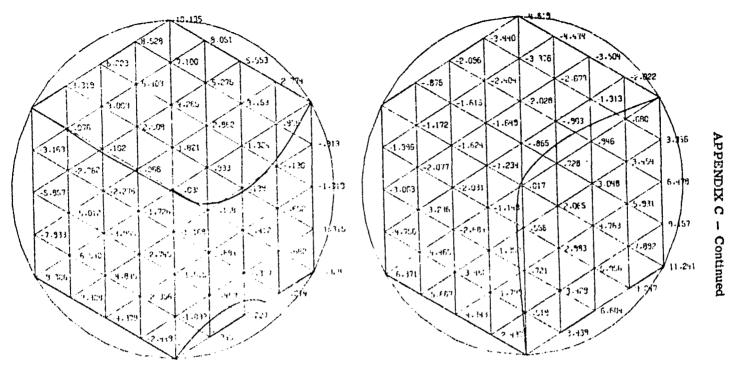
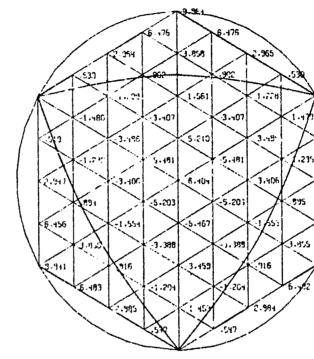


Figure Cl.- Mode 1 of the thin mirror.

Figure C2.- Mode 2 of the thin mirror.



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APPENDIX C

Figure C3.- Mode 3 of the thin mirror.

Figure C4.- Mode 4 of the thin mirror.

Higure Ch.- Made 5 of the thin mirror.

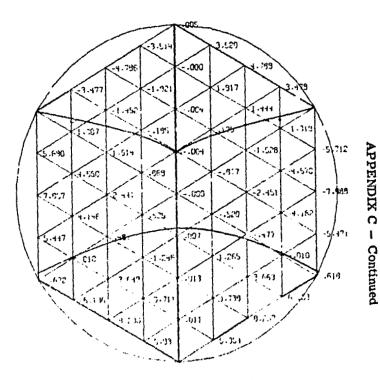


Figure C6.- Mode 6 of the thin mirror.

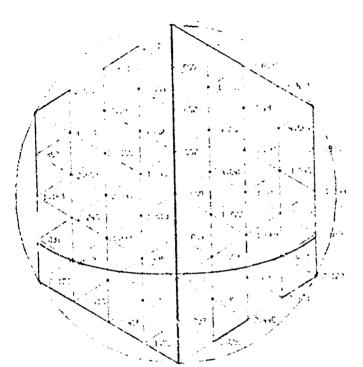
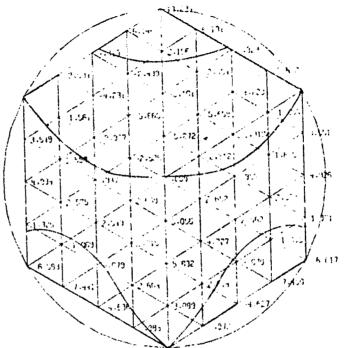


Fig. re C7.- Mode 7 of the thin mirror.



APPENDIX C

Continued

Figure C8.- Node 8 of the thin mirror.

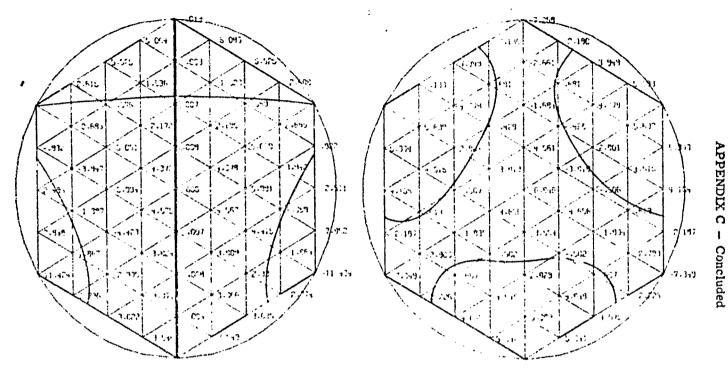


Figure C9.- Bide 9 of the thin mirror.

Figure ClO. - Mode 10 of the thin mirror.

## APPENDIX D

## EIGENVALUES AND MASS MATRE: FOR THE MIRKOR

This appendix contains a listing of the eigenvalues and the diagonal mass matrix m. The SAMIS program eigenvalues are inversely proportional to frequency squared and may be converted to frequency (in hertz) by the following relationship:

$$f_i = \frac{1}{2\pi} \sqrt{\frac{0.97 \times 10^{-4}}{\Lambda_i}}$$
 (i = 1, . . ., M)

The elements of the mass matrix have the units of lb-sec2/in.

The eigenvalues of the U matrix are

(1 ) ACCPA	=	3.511-02	LAMBDA(30) =	5.298-05
LAMADAL 21	2	3.515-02	EAMADA(31) =	5.10F-05
LAMBOA( 3)	*	3.46E-42	LAMBOAL321 =	5.1QF-05
LANBUAL 41	=	2.456-03	LAMBOA(33) =	4.50F-05
LANGEAL DI	2	2.514-93	(AMBDA(34) =	3.885-05
LAMOUAL OF	=	<b>さゃっけたーひろ</b>	LAMHEA(35) =	3.88F-05
LAMSOAL 71	z	2.50と-03	LAMBEA(36) =	3.59F-05
LA48 JAL B)		8.90t=04	LAMADA(37) =	3.35F-05
LAMOUNAL ST	æ	3.40E-114	= 156 }AG6MA 1	3.358-05
LAMOUALINI		2.67E-04	LANHO4(39) =	3.22F-05
LAMBOALLL	4	** 891-04	LAMBOALWOT =	2.95E-05
LAMBEALLES		+. 646-04	LAMBDA(41) =	2.80F-05
LAMBEALLJI	*	3.435~34	LAMBER1471 *	2.765-05
LIMBUALLA	2	J.445-34	[AMHCA(43) =	2.75F-05
CAMBUALLET	#	2.305-134	£24832144} =	2.475-05
LAMBUALLES	2	1.80:-04	1 AMBBA(45) =	2.23F-05
LAMBUALLTE		1.801-04	(A440A(46) =	2.23F-05
LaMS JA ( Lu)		1.746-04	LAMMCA(47) =	2.05F-05
F 7 40 C 7 ( F 4)	¥	1.706-04	[A480A[48] =	2.05F-05
LUSTALICHE		1.305-34	LAMBEA(491 =	2.01F-05
LAMBOALZII		1.4102-04	FAHADA(50) =	2.01F-05
LATOUALEZI	*	1.066-04	LAMBDA(511 =	1.968-05
L=430A(23)	z	3, 15t -13 >	LAMBOA(52) =	1.865-05
L 148 CA (24)		4.100-05	LAMHCA1531 =	1.60f-05
LHASCALLET	3	7.501-05	LAMBDA(54) =	1.60F-05
LAMBUALZE	=	7.48L-95	(AMBCA(55) =	1.58F-05
E448LA(27)	4	1.065-05	E AMMDA(56) =	1.58F-05
LASSIACERIA	۵	J. 808-05	LAMBDA(57) =	1.316-05
LAND DATE OF	*	3.24E-05	EAMBDAESBE =	1.31F-05

# APPENDIX D - Concluded

# The elements of the diagonal mass matrix are

MASS( 1+ 1) =	1.195-03	4455(30+30) :	1.25E-03
4ASS( 2. 2) =	1.258-03	4ASS(31.31) =	1.25E-C3
44551 3. 31 =	1.198-63	MASS(32,32) :	1.25E-C3
MASS1 4, 4) =	1,435-63	MASS(33,331 :	1.19E-C3
4455( 5. 5) =	1.25E-C3	MASS (34.34) =	1.436-03
MASSE 6. 61 =	1.25E-03	MASS(35,35) 4	1.25E-03
MASSE 7. 71 =	1.25E-03	MASS(36,36) 4	1.25E-C3
4455( 8. R) =	1.43E-03	MASS (37.37)	1.25E-C3
MASSE 9. 0) x	1.19E-C3	4ASS(38,38) =	1.438-03
MASSE10.101 =	1-25E-03	4855(39,39)	1.25E-C3
MASS[11.11! =	1.25E-C3	4ASS(40.40)	1.25E-03
HASS(12.12) =	1.25E-C>	MASS (41.41)	1.25E-C3
MASS(13.131 *	1.25E-G3	MASS(42,42)	1.25E-C3
WASS(14.14) =	1.25E-C3	445S(43,43) :	1.19E-63
MASS(15.15) =	1.19E-C3	4A55144.443 1	1.258-03
MASSI 1/ . 163 =	5.50E-C4	MASS (45.45)	1.252-03
MASS(17.17) =	1.258-03	#ASS(46,46) :	1.25E-0?
MASS(18,18) =	1.25E-C3	MASS (47.47)	1.25E-C3
MASS(19.19) =	1.25E-03	MASS(48,48)	1.25E-03
*ASS(20.20) =	1.25E-C3	MASS(49,49) :	1.25E-C3
MASS121.211 =	1.25E-03	MASS(50.50)	1.258-03
MASS122+221 =	1.256-03	MASS (51,51)	1.19E-C3
MASS(23+231 =	1.25E-C3	4ASS(52.52) :	1.198-03
MASS(24+24) =	5.50E-C4	MASS(53,53) :	
MASSE25 + 251 =	1.19E-C3	4ASS(54.54)	1.19E-C3
MASS(26+26) #	1.258-03	4ASS(55,551 :	
4455(27+271 +	1.25E-C3	4ASS(56.56)	1.19E-C3
HASS128+281 =	1.25E-03	MASS (57+57)	1.43E-C3
MASS(29.29) #	1.25E-C3	4ASS(58.581 :	1.196-03

#### APPENDIX E

#### BEST ACTUATOR LOCATIONS - DETERMINISTIC CASE

This appendix contains an enumeration of actuator locations which were found to produce minimum error when the errors were considered to be completely known (deterministic) and nonvarying (figs. E1 to E12). Each figure contains 10 diagrams which show the best 10 actuator locations for one of the three error examples and a specific number of actuators. Grid numbers for the actuator locations can be found by comparison with the numbered pattern in the lower right-hand portion of each figure. The values of the final error for the modal control law and the optimal control law are given beside each figure in the form

 $\frac{A}{B}$ 

where A is the error under the modal control law and B is the error under the optimal control law. These final errors are those given by the square root of equation (53), which requires that these values be multiplied by 0.40 to obtain rms error in microinches or by 0.019 to obtain rms error in wavelengths.

A particular point of interest occurred in figure E10 (two actuators, error example 3). In this figure the  $\rm\,H^N\,$  matrix was decidedly ill conditioned for most of the examples. The normalized determinant was as low as  $6\times 10^{-5}$  and the best value was  $3.5\times 10^{-2}$ . If this case arose in practice, it would be best to look at three actuators or more. In figure E11 (three actuators) the normalized determinant was of the order of 0.3, which is very good.

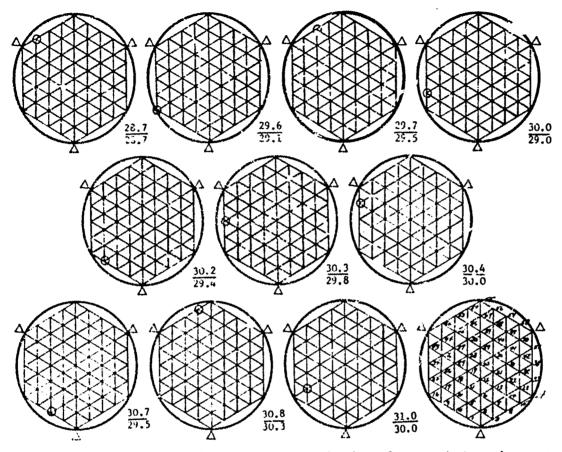


Figure F1.- Actuator locations which minimize the rms error of the mirror for one actuator and error example 1.

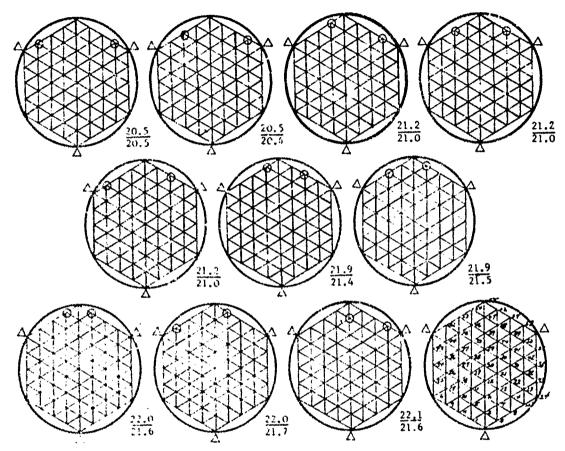


Figure FO.- Astract r 1 continue which minimise the rmo err r of the mirror for two activators and error example 1. --

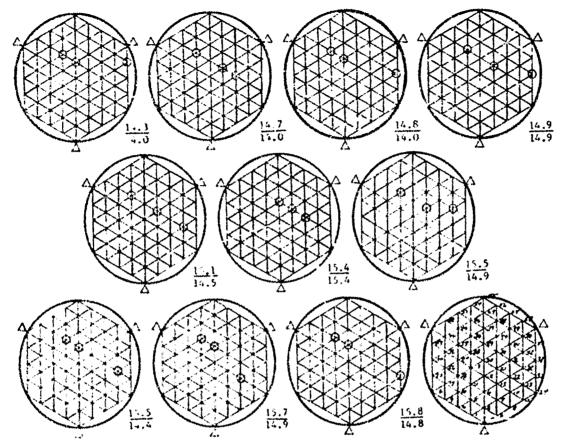


Figure 14.- Activities has discovered which mislains the reservor of the mirror for three actuators and error example 1.

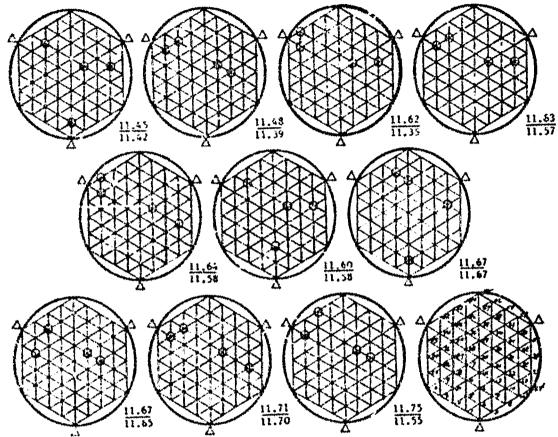
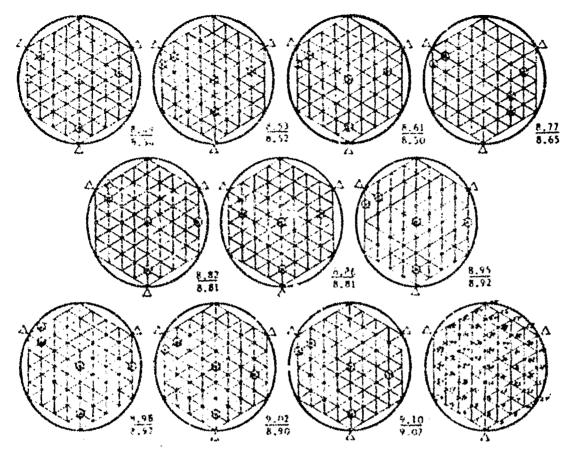
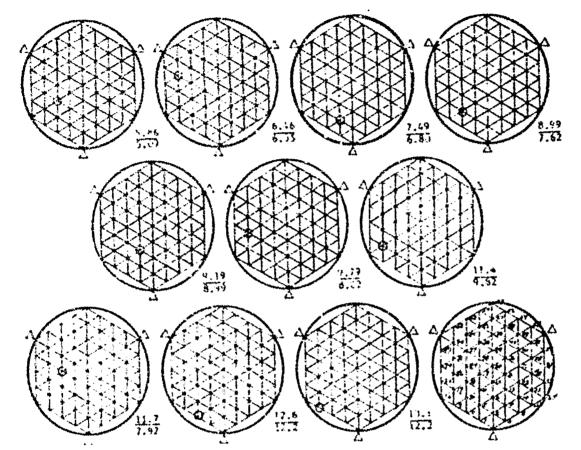


Figure Fb. - Actuator locations which minimize the rms error of the signor for four actuators and error example 1.



Higher than Access to Incitious which whan so the part error of the abroad up that so that so and error example I.



Tighter than a turner is not an which meanths the test that the street street for an older and electrosterist ca

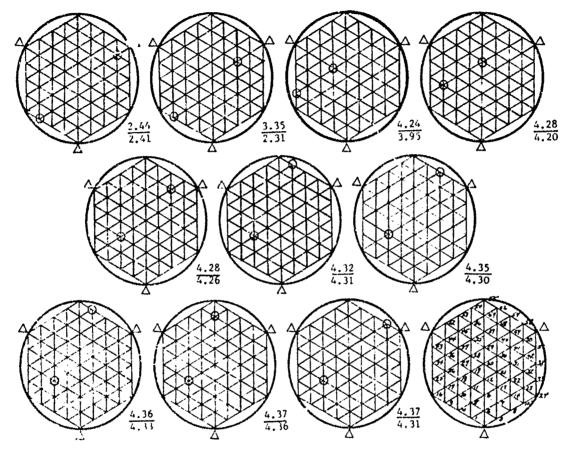


Figure 17.- Actuator locations which minimise the rms error of the mirror for two actuators and error example 2.

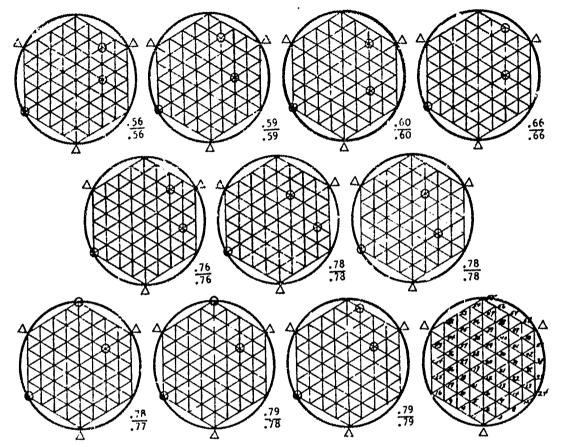


Figure F8.- Actuator location, which minimise the rms error of the mirror for three actuators and error example 2.

\*

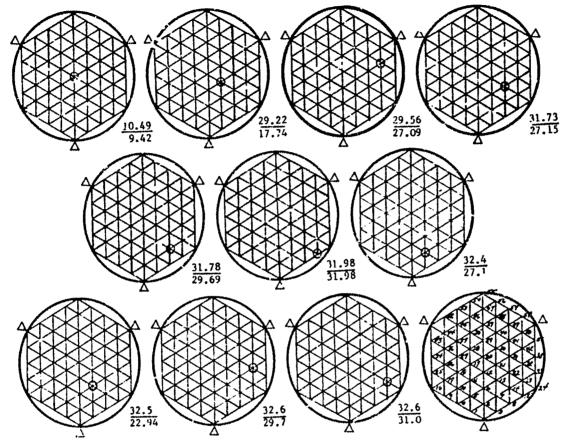


Figure 19.- Actuator locations which minimize the rms error of the mirror for one actuator and error example 3.

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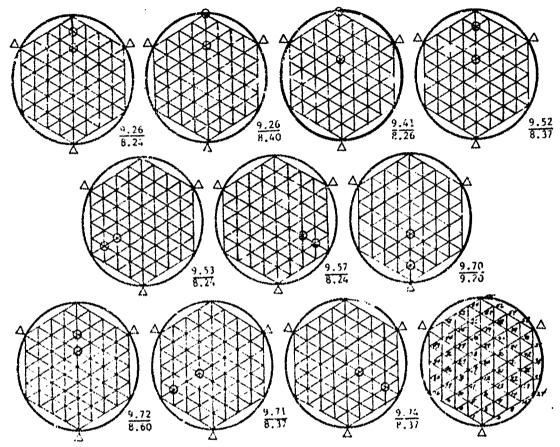


Figure F10.- Actuator locations which minimize the rms orror of the mirror for two actuators and error example 3.

Problem is explicably sets of the inter-

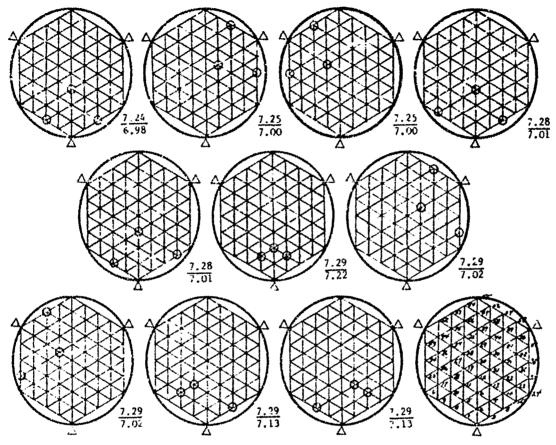


Figure Fil.- Actuator locations which minimize the rms error of the mirror for three actuators and error example 3.

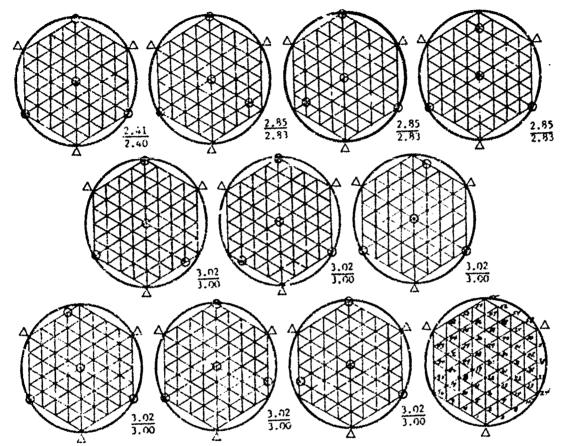


Figure E12.- Actuator locations which minimize the rms error of the mirror for four actuators and error example 4.

## APPENDIX F

### BEST ACTUATOR LOCATIONS - UNCORRELATED ERRORS

This appendix contains an enumeration of actuator locations which were found to generate minimum error under the modal control law (figs. F1 to F5). These were obtained by using the errors of example 1. The answers are given beside each diagram in the figures in the following form:

ABC

where

- A the error predicted by equation (61) assuming all values of  $\phi_{ ext{iN}}^2$  are 0
- B the error obtained from equations (53) and (29)
- C the error under the optimal control law

The performance index is duat obtained from the square root of equation (53) and must be multiplied by 0.49 to obtain rms error in microinches or by 0.019 to obtain rms error in wavelengths.

Selecting other error examples would, of course, result in the selection of different actuator locations; however, it can be seen from the values of  $\phi_{1N}^2$  in table II that the effect of a different actuator location could not make the final answer much better because the values of  $\phi_{1N}^2$  are already very small. For this reason the searches for actuator locations were restricted to the one example. The searches for one to four actuators inclusive considered all possible combinations, whereas those for seven actuators considered only a small subset of all possible combinations. This subset was chosen from those locations near the nodes of the next three higher order modes. This reduced the number of runs required to a reasonable value and resulted in a selection of actuator locations which were reasonably close to the theoretical limit.

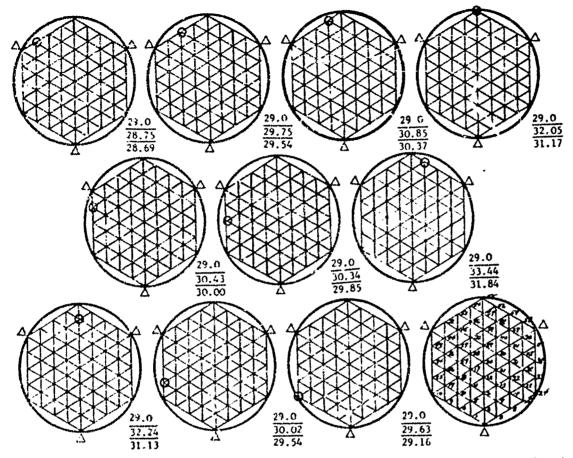


Figure F1.- Actuator locations which minimize the error generated by the control system in driving the first made to zero whise one actuator. From distribution is taken from error example 1.

Position in

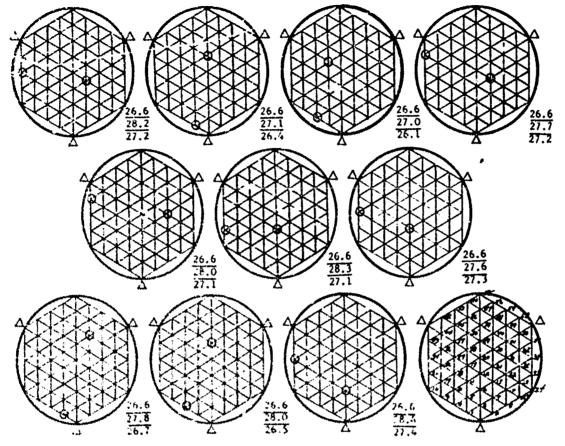


Figure tive detuator locations which minimize the error ponerated by the control system in driving the first two moles to dero large two not control. From distribution is taken from error example 1.

5. 4.

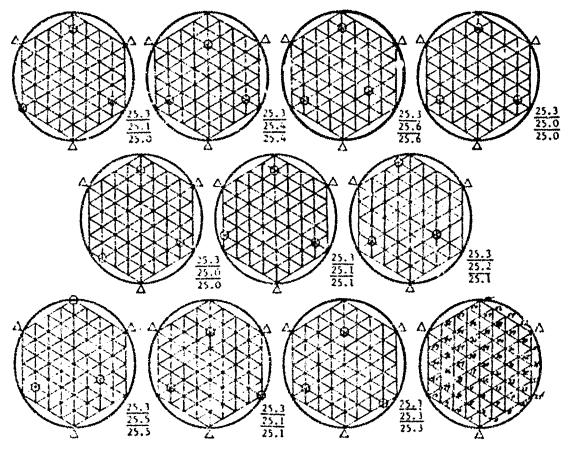


Figure 1%- Actuator locations which missing the error personated by the control system in driving the first three modes to some unless three notations. First distribution is taken from error example 1.

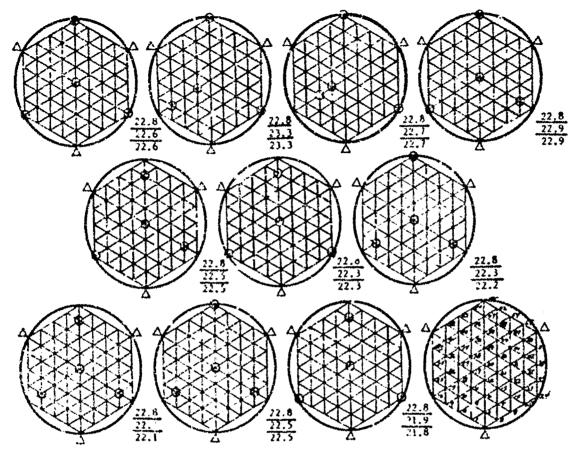
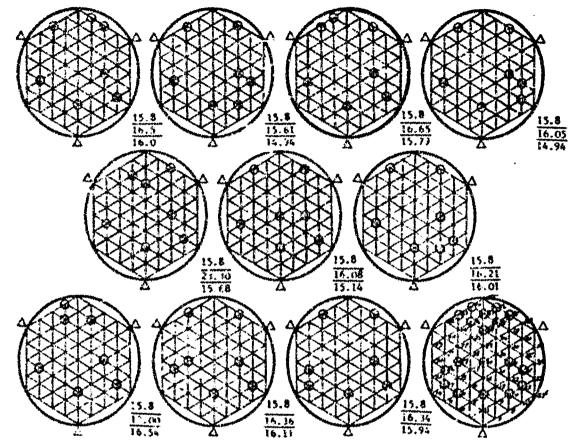


Figure Face Activator locations which minimize the error generated by the control system in driving the first from motes to zero taking four actualons. From Statibution is taken from error example 1.



Tiquee Fin- Actuator locations which resulted in the minimum generated error for error example 1. The following 10 grid points were used in the search procedure: 6, 10, 14, 17, 20, 25, 26, 27, 31, 52, 17, 46, 47, 48, 15, 54, 56, and 57.

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TABLE 1.- MODAL CONFFICIENTS FOR EXAMPLE FIGURE ERRORS

Mode number		i e w coefficients :	
MOSE DEDIDEL	Error example 1	Error example 2	Error example :
ţ	-17.18	-19.47	0,23
2	-12,10	-15.40 -22.54	13
3	.1.44	-22.54	30,93
4	-11.00	1.91 .57	13.79 .02
3	-3,67 3,76 -12.70	- 30	,00
Ÿ	-11.70	20 -1.71 72	*****
ė.	• 1,50° 1	72	*****
9	2,93	1.37	*****
16	-17.56	-,24	-,49
11	.92	-, (4)	*****
12	w.91	.03	01
13	21	.22	442424
14 15	1.04 5.38	.21 07	1.17
16	1.14	- 76	****
17	.51	.01	****
15	-1.39	.04	*****
19	-#.04	.20	<b></b> ♥
20	-1,18		*****
21	.va -2.79	.05	*****
22	-2.79	.04	*****
73 24	*.28	.03	****
73	.05 -1.22	.13	*.176
26	4,56	,01	7,644
24	- 10	.03	******
25	-5.73	.13	553
29	,5≇	*****	-,61
30	.94	.03	*****
#1	<b>ેલ</b> :	****	*****
32	. 63	.03	*****
33	.25	*****	*****
34 35	*,05 * 78	.01	*****
34	-1.35	.41	63
27	7.5	*****	
24	.60 +.09	.ላን	*****
3#		****	*****
46	.57	,62	*****
41 42	.37	*****	******
42	.57 • 78	*****	*****
45 44	5	03	*****
45	.00	01	
46	.04	*****	*****
47	+.32	03	*****
44	,14	04	*****
4#	44	*******	*****
54	,26	*****	*****
\$1	.44	,04	-,68
37	.06	*****	*****
ii ii H	. 2	0:	******
<u> </u>	. 19	7,44	*****
10 54 67	.25	****	*****
4.7	+. <b>≥</b> ≎		*****
54	.03	-,01	
$\sum_{i=1}^M \tau_i^2$	1134.6	1135.7	1135.1

# TABLE II.- VALUES OF $\phi_{1N}^2$ FOR N = 1, 2, 3, 4, AND 7

Determined for error example 1; actuator grid locations corresponding to these values are tabulated below the values of  $\phi_{iN}^2$ 

Mode	$\phi_{i1}^2$	$\phi_{\mathbf{i}2}^{2}$	$\phi_{\mathbf{i}3}^{2}$	$\phi^2_{i4}$	$\phi_{\mathbf{i7}}^{2}$
1	0.29	2.011	1.46 × 10 <sup>-3</sup>	$1.35 \times 10^{-3}$	2.1 × 10 <sup>-2</sup>
2		3.336	$7.58 \times 10^{-4}$	1.35 × 10-3	8.6 × 10-3
3			$1.41 \times 10^{-2}$	9.8 × 10 <sup>-4</sup>	9.7 × 10-4
4				4.4 × 10 <sup>-3</sup>	2.60
5					0.541
6					7.94
7					1.51
Actuator grid locations	52	34, 21	16, 23, 47	16, 20, 24, 55	6, 23, 26, 31, 53, 56, 57

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